# 13

# *Hydrological Responses to Changes in Forest Cover on Uplands and Peatlands*

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## Introduction

Long-term data are used to quantify how ecosystem disturbances such as vegetation management, insect defoliation, wildfires, and extreme meteorological events affect hydrological processes in forested watersheds (Hibbert 1967; Swank et al. 1988; Likens and Bormann 1995; Lugo et al. 2006). The long-term, paired-watershed approach has been used at many sites to measure the effects of vegetation manipulations (e.g., harvesting and cover-type conversions) on stream-water yield. When data from multiple studies and diverse ecosystems are compared, worldwide results show that (1) increases of water yield are detectable when 20% or more of forest basal area is harvested and (2) the magnitudes of responses vary among sites due to differences in the percentage of the watershed that was affected by afforestation and reforestation (Hibbert 1967; Bosch and Hewlett 1982; Hornbeck et al. 1993; Stednick 1996; Brown et al. 2005).

Paired-watershed studies in forests of the United States are widely dispersed, span climate extremes, and are typically located in steep, mountainous headwaters. To fill a gap in the USDA Forest Service network of research watersheds, the Marcell Experimental Forest (MEF) was established during the 1960s in an environmental setting in north-central Minnesota that is distinct from the steep mountainous terrains of other experimental forests (Bay 1962). The MEF has little topographic relief, no dominant aspect, abundant peatlands, and a climate that is continental with long, cold winters (Chapter 2). Relative to steep upland watersheds, the magnitude and timing of peak streamflow are lagged and attenuated due storage in wetlands such that runoff responses to rainfall or snowmelt events are longer in duration and peak streamflow is lower (Bay 1968; Verry 1997). These characteristics are common in boreal ecosystems that span northern latitudes including headwaters in postglacial landscapes of the northern Lake States of Minnesota, Wisconsin, and Michigan. Studies at the MEF were initiated to investigate the unique physical, silvicultural, and hydrological aspects of lowland ecosystems where uplands drain to peatlands, streams, and lakes (Chapter 1).

## Peatland Watersheds at the MEF

The landscape at the MEF is a mosaic of lakes and peatlands interspersed among low-elevation hills that were deposited as glacial moraines (Wright 1972). Sandy glacial outwash overlies Precambrian greenstone bedrock, is up to 50 m deep, and forms a regional groundwater aquifer across north-central Minnesota. A thin till layer tops much of the sandy outwash. The surficial soils on uplands are sandy loams above clay loams that are permeable but

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retard the vertical flow of water. In low-lying areas underlain by the clay loam aquitard, shallow postglacial lakes slowly filled with peat (Histosols) as partially decomposed organic matter accumulated under saturated and anaerobic conditions (Boelter and Verry 1977).

The six research watersheds at the MEF have uplands that route upland runoff waters to central peatlands. Each watershed is 12%–33% peatland by area and drains to series of downgradient wetlands, lakes, and streams via a short intermittent or perennial stream (Bay 1968). All the peatlands in the research watersheds receive water inputs from precipitation and runoff from the surrounding upland mineral soils whether perched above or embedded in the regional groundwater aquifer.

Fens are minerotrophic peat-forming wetlands with inputs of water from regional aquifers. The peatland in the S3 watershed is a fen, and the stream draining S3 flows perennially unlike the S1, S2, S4, S5, and S6 research watersheds, which are perched several meters above unsaturated sands and the regional aquifer.

Because a confining till layer separates perched watersheds from the regional aquifer and groundwater inputs, water in perched watersheds originates solely from precipitation falling on the peatland and surrounding upland soils (Chapter 7). In these hydrogeologic settings, ombrotrophic peat-forming wetlands, such as those in the S1, S2, S4, S5, and S6 watersheds, are bogs (Chapter 4). Clay layers route runoff water from the overlying silty loams via lateral flowpaths into lagg zones that surround raised dome bogs (Timmons et al. 1977; Verry and Timmons 1982; Tracy 1997). Streams drain the lagg zones, and streamflow usually stops during dry summers and autumns. During winter, streamflow has stopped every year on record (Chapter 2). Despite low-hydraulic conductivities, up to 40% of annual precipitation inputs to the perched peatlands may recharge the regional groundwater aquifer via deep seepage through the clay aquitard (Nichols and Verry 2001), primarily through clay loam tills under the lagg zones of bogs (Chapters 4 and 7).

Conifer forests were prevalent throughout northern Minnesota before European settlement. Cutting of uplands forest was widespread during the late 1800s and early 1900s. After harvesting and subsequent fire suppression, much of the former white (*Pinus strobus*), red (*Pinus resinosa*), and jack (*Pinus banksiana*) pine forest is now a primary succession forest of trembling aspen (*Populus tremuloides*), bigtooth aspen (*Populus grandentata*), paper birch (*Betula papyrifera*), and balsam fir (*Abies balsamea*) with other mixed northern hardwoods. Stand types, stem densities, and basal areas were surveyed for uplands and peatlands in each watershed during 1968 (Verry 1969) as summarized in Table 13.1.

Aspen-dominated stands and pure aspen stands grow prolifically on uplands soils throughout the region. Aspen is typically harvested by whole-tree clearcutting during winter on frozen soils and during summer on dry soils to minimize soil disturbance. Aspen is merchantable after 40–60 years of growth, and forests are actively managed throughout the region for the

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**TABLE 13.1**

Stand Age, Stem Density, and Basal Area in Uplands and Peatlands at the Time of the 1968 Vegetation Survey

| Watershed | Stand Type | Stand Ages | Stem Density (Stems $ha^{-1}$) | Basal Area ($m^2$ $ha^{-1}$) |
|---|---|---|---|---|
| *Uplands* | | | | |
| S1 | Two aspen stands | 44 and 52 | 645 | 22.0 |
| S2 | Aspen with red maple and paper birch | 50 | 480 | 23.2 |
| S3 | One aspen and two jack pine stands | 51, 52, and 64 | — | 37.6 |
| S4 | Aspen | 49 | 645 | 21.8 |
| S5 | Two aspen, aspen-birch, two spruce-fir, red and white pine, mixed hardwood, and cedar stands | 48 (aspen) and older (other stands) | — | 13.5–49.8 |
| S6 | Aspen | 56 | 356 | 29.6 |
| *Peatlands* | | | | |
| S1 | Black spruce | 62 and 73 | 3520 | 7.0 |
| S2 | Black spruce | 99 | 1759 | 13.3 |
| S3 | Black spruce | 100 | 685 | 14.0 |
| S4 | Black spruce | 49 | 188 | 15.2 |
| S5 | Black spruce | 100 | 1055 | 13.3 |
| S6 | Black spruce and tamarack | 64 | — | 12.4 |

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

pulp industry (Bates et al. 1989) or to restore conifer cover to aspen-covered lands. To convert to a conifer forest in the absence of wildfires, excessive growth of aspen and other competitors in clearcuts must be managed, usually by controlled burns, herbicides, or mechanical treatment.

Black spruce (*Picea mariana*), eastern tamarack (*Larix laricina*), and northern white cedar (*Thuja occidentalis*) grow in the overstory of forested peatlands. Trees in bog forests often are even-aged, probably as a result of regeneration after wildfires or other catastrophic disturbances such as straight-line windstorms and tornados (Clark 1990).

## Hydrological Measurements

The six research watersheds were instrumented during the 1960s with outlet streamflow gages, peatland water table wells, and precipitation gages to study

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the effects of forest management on water yield. The watersheds, instrumentation, and measurements are detailed in Chapter 2. Daily water table levels were measured at central wells in each peatland. Streamflow was initially measured at each watershed, and stage-discharge relationships or regressions between peatland water table level and stream outflow were used to calculate stream discharge. A water year begins on the first of March and ends on the last day of February of the following calendar year. This water year reflects the annual water cycle of Minnesota bog watersheds where intermittent flow starts during spring snowmelt and typically stops during winter. Average annual water yield ratios were calculated for each water year by dividing stream-water yield by precipitation and averaging annual values.

Daily precipitation is measured in forest clearings in the S2 and S5 watersheds (Chapter 2). Annual precipitation is calculated for water years that begin on November 1 and end on October 31, which reflects the accumulation of snow starting in November that does not contribute to streamflow until snowmelt the following spring.

### Comparisons of Responses at Experimental and Control Watersheds

Responses of annual stream-water yield from harvest treatments at the S1, S3, S4, and S6 watersheds are compared to the S2 and S5 control watersheds with unmanipulated upland and peatland forests. We consider water yields to be significantly different from preharvest conditions during postharvest years and decades that exceeded the 95% confidence intervals about the regressions, or if regressions slopes significantly differed (ANCOVA where $p < 0.05$). Peak daily water yields were compared between harvested and control watersheds to assess changes in peak flow response to forest harvesting. Peak flow responses were compared during snowmelt and rainfall-runoff events (June–October). This approach, though not a generalizable test of peak flow responses due to stochasticity of long-return-interval storm events, may show responses to the specific watershed experiments.

The 9.7 ha S2 watershed has a 3.2 ha peatland. During water years from 1961 to 2008, annual precipitation at the meteorological station (South) in the S2 watershed averaged 76.9 ± 11.1 cm year$^{-1}$ (mean ± 1 standard deviation). Mean stream-water yield from water years 1961 to 2008 was 16.7 ± 5.5 cm year$^{-1}$, and the mean runoff ratio was 21% ± 6%. When inventoried in 1967 before any harvest, mean basal area of the aspen dominated stand was 23.2 m$^2$ ha$^{-1}$, and the stand was 50 years old (Verry 1969). The basal area of black spruce in the S2 peatland was 13.3 m$^2$ ha$^{-1}$, and the average age was 99 years during 1968.

The S5 watershed is 52.6 ha. Upland soils and five small satellite wetlands drain into a 6.1 ha central peatland. Mean stream-water yield from 1962 to 2005 was 10.9 ± 4.2 cm year$^{-1}$, the mean runoff ratio was 13% ± 4%, and mean precipitation was 78.6 ± 11.2 cm year$^{-1}$. The stream-water yield from the S5 watershed is less than at the S2 watershed, because 5 ha of the S5 upland soil

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is deep sand and that area may recharge directly to the regional groundwater table. In 1968, the S5 uplands had stands of aspen (two age classes), spruce-fir, red and white pine, mixed hardwoods, and white cedar. Mean basal area was 23.6 $m^2$ $ha^{-1}$, and the average age was 100 years (Verry 1969).

## Hydrologic Responses to Upland Harvests

Studies at the MEF were designed to determine the effects of upland-only harvests and peatland-only harvests. This information was needed to maintain forest productivity, understand water-yield responses to forest management, and maintain water quality in lowland watersheds with uplands that drain to peatlands. Even when peatland vegetation is not disturbed by upland tree harvesting, watershed-scale hydrologic responses are influenced by the routing of water through peatlands on the way to the watershed outlet. The effects of upland tree harvesting on the hydrology of undrained peatlands had not been quantified before manipulative watershed studies were initiated at the MEF in the 1970s.

Bog water table elevations are controlled by lateral outflow via streams as well as vertical fluxes to the underlying regional groundwater system via deep seepage and the atmosphere via evaporation and transpiration (Chapter 7). If increased water flows to peatlands from hillslopes after upland clearcutting and vegetation change, bog water levels may fluctuate more in response to changes of water inputs from upland source areas. In particular, maximum bog water levels may increase if lateral inflow of upland runoff water from hillslopes increases after clearcutting. However, if high water levels are in contact with the shallow root systems of bog vegetation, evapotranspiration may increase resulting in a negative feedback that may mask any changes of annual water yield.

### Harvest and Regeneration of an Upland Aspen Forest

The 25.9 ha upland of the S4 watershed was harvested from 1970 to 1972. Hydrologic responses to the S4 upland clearcut previously were reported for the first year after the clearcutting (Verry 1972), updated later to include the first 9 years after the clearcut (Verry et al. 1983), and updated again to include the first 15 years after the clearcutting (Verry 1987). Herein, we interpret hydrological responses based on 35 years of post clearcutting data that spanned the regrowth of the aspen forest to the stage of full aspen stocking.

The S4 watershed is 34.0 ha. The central 8.1 ha is a black spruce peatland that surrounds a 0.4 ha open bog and a small pond. Mean stream-water yield before clearcutting was 19.4 ± 5.1 cm $year^{-1}$ (±1 standard deviation), and the ratio of precipitation to stream runoff was 25% ± 5%. Prior to clearcutting, the

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upland forest was predominantly a 52 year-old mature aspen stand. Mean basal area of the S4 and S5 uplands was similar prior to clearcutting (Table 13.1). About 2% of the upland forest was a mixed cover of 57 year-old paper birch and aspen. At the time of cutting, basal area was 21.8 $m^2$ $ha^{-1}$, and aspen biomass was 240,000 kg $ha^{-1}$.

All merchantable timber taller than 3.0 m was cut and removed from the S4 uplands (Figure 12.12). The first 1.3 ha of forest were clearcut during December 1970 on an area northeast of the peatland. Clearcutting west of the peatland continued through winter and about half of the upland area, or 34% of the total watershed area, was clearcut before snowmelt in 1971. The remaining upland forest was clearcut from September 1971 to January 1972. By September 1971, 70% of the annual stream-water yield already had occurred. The progression of the clearcut provided an opportunity to assess the effects of partial (water year 1971) and total (post-1971) upland clearcutting on stream hydrological responses (Verry et al. 1983; Verry 1987). All noncommercial trees larger than 8.9 cm in diameter at breast height (dbh) were felled and left in place. Because the black spruce forest on the central peatland of the S4 watershed was not harvested, the completed aspen clearcutting included 71% of total watershed area. Disturbance from road and major skid trails affected less than 2% of the watershed area (Verry et al. 1983). Logging slash was left in place, and the tangled branches finally settled to the forest floor about 6 years after clearcutting (Verry 1987).

Aboveground tree biomass was surveyed during 1968, 1971, every 2 years from 1972 to 2002, and again during 2008. Aspen regrowth from root suckering was rapid. Aspen tree density was 101,000 stems per ha by August 1971, and the trees were about 2 m tall in clearcut areas (Verry et al. 1983). By the spring of 1979, aspen were about 6 m tall. The biomass of overstory trees greater than 8.9 cm dbh exceeded 90% of the preharvest biomass during 2000 and was similar during 2008.

### *Changes in Annual Water Yield*

Preharvest streamflow data were collected during water years at S4 and S5 from 1962 to 1970. To determine effects of the uplands clearcut and model, a "no clearcutting" scenario, predictions of annual stream-water yield at the S4 watershed were calculated for water years from 1971 to 2006 using a regression equation relating preharvest stream-water yield between S4 and the S5 control watershed:

$$Q_{\text{S4-predicted}} = -46.0 + 36.7 \times Q_{\text{S5}}^{0.25}, \ \left(R^2 = 0.99, \ p < 0.0001\right), \qquad (13.1)$$

where Q is the annual stream-water yield at the S4 or S5 watershed (units of centimeter per year). Stream-water yield during 1970 was included in the precalibration dataset, because less than 5% of the watershed area was

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harvested during December 1970, most of the annual water yield occurred during snowmelt during the preceding spring, streamflow stopped on 28 December, and streamflow during the December harvesting was less than 1% of the annual stream-water yield. Change in annual stream-water yield was calculated for each water year by subtracting the predicted from the observed annual water yield:

$$\Delta Q_{S4} = Q_{S4\text{-observed}} - Q_{S4\text{-predicted}}, \quad (13.2)$$

A positive $\Delta Q_{S4}$ indicates an increase of stream-water yield relative to the preharvest period. Hydrological responses during the clearcut and early regrowth period from water years 1971 to 1979 and the postclearcut decades from water years 1980 to 1989 and 1990 to 2005 were compared to the pre-clearcut stage from water years 1962 to 1970.

Prior to the harvest, the difference between measured and predicted annual water yield ranged from −4% to +5% with a mean difference of 0% ± 3% (Figure 13.1). During the first postharvest water year when 34% of the watershed area was clearcut, annual stream-water yield increased by 25% relative to S5 (Verry 1972). Beginning during the second water year (1972) when 71% of the watershed area had been clearcut, annual water yield was 38% higher relative to the preharvest period and remained higher until water year 1982 (Figures 13.1 and 13.2). During water years from 1971 to 1979, the mean increase in stream-water yield was 22% ± 10%. The change in yield ($\Delta Q_{S4}$) ranged from −10% to +18% and averaged +0% ± 8% during water years from 1980 to 1989. The $\Delta Q_{S4}$ ranged from −22% to +16% and averaged −7% ± 11% during water years from 1990 to 2005. The recent decrease in annual water yield occurred when biomass had regrown to the level of the preharvest forest, and the site index exceeded the original stand by 2 m (Chapter 12).

### *Changes in Peak Flow to Snowmelt and Rainfall*

If clearcutting affected precipitation inputs by changing snow accumulation and ablation, peak streamflow responses during snowmelt would also be expected to change. During the first postharvest snowmelt (April 1971), when the uplands were partially clearcut at the S4 watershed, the magnitude of snowmelt peak streamflow was 35% less than predicted from streamflow at the S5 control watershed (Verry 1972). Snowmelt began 2 days earlier relative to the S5 control watershed and streamflow peaked twice in contrast to the single peak at S5. The timing of snowmelt likely changed due to earlier melting of snow along the exposed road and runoff of that snowmelt upstream of the S4N weir. During April 1972, when the uplands were completely clearcut, the snowmelt runoff peak more than doubled the predicted peak and streamflow peaked 4 days earlier than that at the control (Verry 1972).

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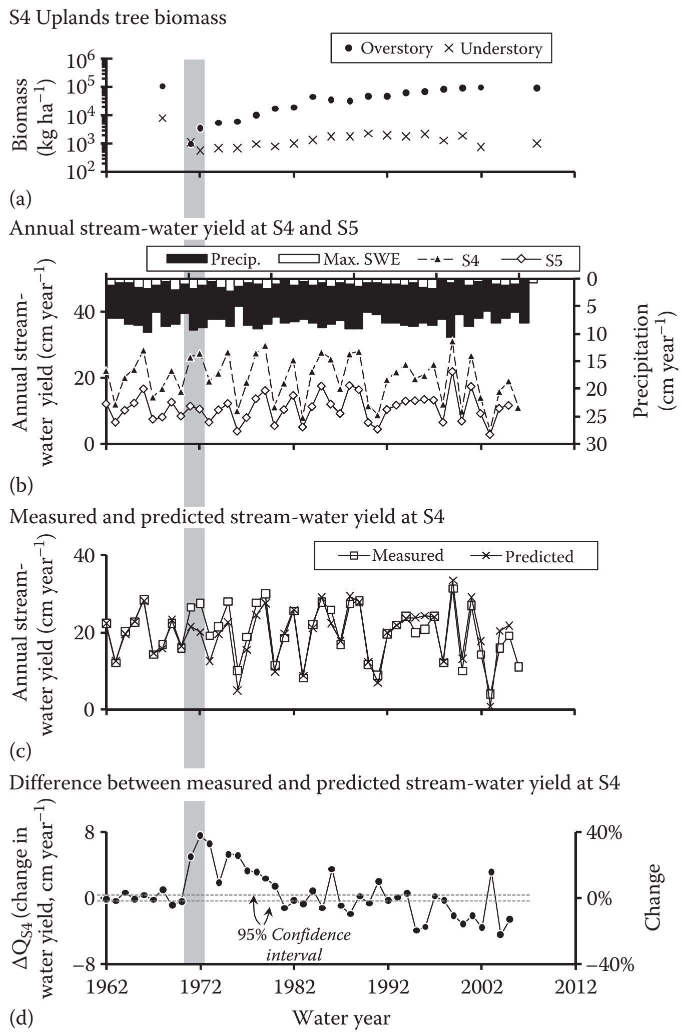


**FIGURE 13.1**
Uplands tree biomass (a); annual precipitation, maximum snow water equivalent (SWE), and annual stream-water yield from the S4 and S5 watersheds (b); observed and regression model predictions of annual streamflow at S4 (c); and difference in water yield between observed and predicted streamflow (d). Overstory biomass includes trees more than 8.9 cm diameter at breast height, and understory biomass includes woody vegetation less than that dbh. The shading shows the timing of clearcutting from winter 1970 and spring 1972.

When the first two snowmelt responses were considered within the 1971–1979 postharvest period, there was no detectable change in peak stormflow magnitude during snowmelt (Figure 13.3a), suggesting a short-term net effect on snow interception, sublimation, and melt. The differences between the first snowmelt with a complete clearcut and subsequent years highlight

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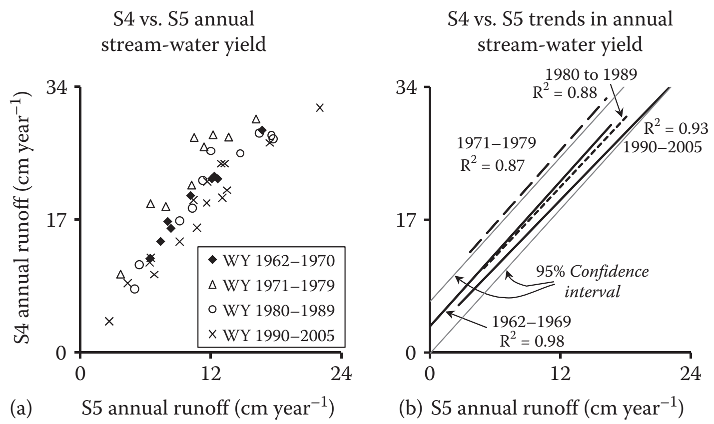


**FIGURE 13.2**
Relationships of stream-water yield between the clearcut S4 and the S5 control watersheds. Annual stream-water yield changed in the water years after harvest (1971–1979) relative to preharvest water years (1962–1970) and decades after harvest (1980s, 1990s, and 2000s). Annual data (a), and trends (b) by response period.

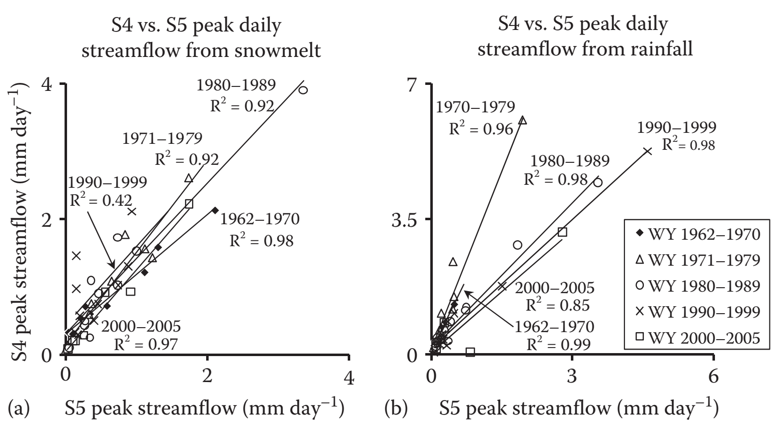


**FIGURE 13.3**
Peak daily stream-water yield from snowmelt (a) and rainfall (b) during each water year, relationships between the clearcut S4 and the S5 control watersheds during the preclearcut (1962–1970), clearcut (1971–1979), and postclearcut periods (1980 and after).

different responses from a cleared condition (e.g., pasture or shrub land) to a regenerating aspen forest (see Chapter 7).

Clearcutting should affect rainfall–runoff responses during the growing season due to differences in interception, evaporation, and transpiration between mature and regenerating aspen forests. Verry et al. (1983) reported that streamflow peak size doubled during the first 3–5 years after clearcutting (Figure 13.3b). During the 1980s, rainfall–runoff responses reversed

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when forest biomass increased above preharvest levels, and the relative magnitude of peak rainfall–runoff continued to decrease from 1990 to 2005. The timing of storm flow in response to rainfall events did not change (Lu 1994).

### *Changes in Bog Water Levels*

Mean water levels in the S4 bog increased relative to the S5 control watershed during the 1970s after the uplands were clearcut and then decreased during the 1990s when the overstory basal area was about the same as the preharvest period (Figure 13.4). The increase in bog water level reflects increased inflow of upland runoff water from hillslopes after clearcutting.

### *Land Management Implications of the S4 Upland Clearcutting Experiment*

Upland clearcutting at the S4 watershed affected hydrological responses when areas exceeding 34% of the watershed were clearcut. Syntheses of past studies suggest a threshold of about 20% basal area harvesting before effects on stream-water yield are observed (Hibbert 1967; Stednick 1996; Verry 2004).

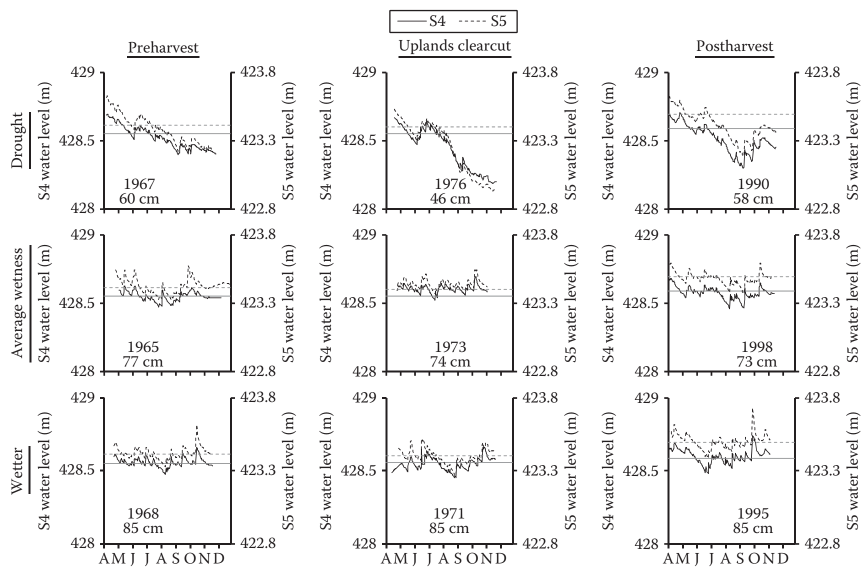


**FIGURE 13.4**
Daily water levels in the S4 bog for preharvest, clearcut, and early regrowth, and third decade of regrowth stages relative to the S5 control watershed. Water levels are shown during drought, average, and above average wetness conditions. The annual precipitation input is shown below the water year. The horizontal lines show the mean bog water level for S4 (solid) and S5 (hashed) during the preharvest water years from 1964 to 1969, during the immediate postharvest water years during the 1970s, and the 1990s when aspen biomass was increasing above preharvest amounts.

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Verry (2004) showed a response curve that included data from the S4 partial and total upland clearcuts. Interpretation of these data indicated little or no increase in stream peak flows until 50% of an aspen-dominated landscape area was cleared. In larger watersheds where 2%–3% of the landscape may be clearcut in a given year such as the managed forests of northern Minnesota, effects of aspen harvesting on streamflow peaks in large rivers would not be detectable, and increases of peak streamflow may not be measurable with distance downstream of small clearcut watersheds.

## Upland Forest Conversion from Hardwoods to Conifers

The upland forest at the S6 watershed was clearcut during 1980 to study effects of harvesting and aspen forest conversion to conifers (Figures 12.6, 12.7, and 13.5). Alternatives to the widespread use of herbicides were being considered at the time, and the S6 experiment was used to evaluate cattle grazing as a forestry tool for site preparation (see Chapter 12). The results, which have not previously been published, show how watershed hydrology responded and provided an example of a management approach to convert forest cover. The 8.9 ha S6 watershed has a 2.0 ha peatland. Prior to harvest, mean annual water yield was 15.1 ± 10.5 cm year$^{-1}$, and the mean ratio of annual stream runoff to precipitation was 19% ± 11%. Aspen was 84% of the overstory while red maple, paper birch, and red oak were each 7% or less of the overstory. The mature aspen stand at the S6 watershed had the lowest preharvest basal area of any research watershed (Table 13.1). The nearly equal mix of black spruce and tamarack cover on the bog was 76 years old, when the uplands were clearcut, and the trees were 12–15 m tall.

The first 2.1 ha of upland forest were commercially clearcut during March 1980. Road restrictions during snowmelt prevented further logging until

**FIGURE 13.5**
The S6 upland clearcut during 1981, facing east. (Photo courtesy of A.E. Elling, USDA Forest Service, Grand Rapids, MN.)

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the remaining 7.1 ha of upland trees were clearcut during June. A Drott feller–buncher was used to shear trees during the whole-tree harvest. The total logged area exceeded the S6 uplands area because the clearcutting extended beyond the watershed boundaries to include an edge buffer. Some logging slash was piled and burned on site but most was removed by full-tree skidding. The aspen clearcut removed trees on 77% of the watershed area because black spruce, tamarack, and other vegetation were not harvested from the peatland.

The watershed was fenced in June 1980 and 12–17 cows, steers, or calves grazed the uplands from September to October 1980, June to September 1981, and June to July 1982 to suppress aspen regeneration by sprouting from root suckering (Chapter 12). Cattle were removed from the S6 watershed when all forage was consumed or trampled. The uplands were relatively free of woody vegetation during the 3 years before conifers were planted (Figure 12.6). The grazing effectively suppressed aspen regeneration and was a viable alternative to the use of herbicide applications. At $247 per ha, the cost was the same as for herbicide application.

After grazing, red pine seedlings were planted on more than 70% of the clearcut on the western end, and white spruce was planted in the remaining area during May 1983. Both species were 4 year-old seedlings at the time of planting, and 2200 seedlings per ha were planted. By 1987, the average height of conifer trees was 43 cm. Survival of red pine was 55%, and survival of white spruce was 81%. Because the growth of willows (*Salix* sp.), paper birch, and hazel shaded conifer seedlings, the herbicide Garlon 4 was sprayed on uplands vegetation on August 1987 after it was decided that additional grazing might damage seedlings.

### *Changes in Annual Water Yield*

Preharvest streamflow data were collected from 1964 to 1979 at the S6 watershed. As a result of the change in the stream gage structure from a flume to a V-notch weir during 1976, water transiently backed into the peatland resulting in higher bog water levels after 1976 (Chapter 2). Consequently, only 4 years of pretreatment data from water years 1976 to 1979 were used to calculate expected water yield, because the pre- and post-1976 data were not comparable. Expected annual stream-water yield was calculated from a regression of preharvest data:

$$Q_{S6\text{-predicted}} = 4.6 - 0.2 \times P + 1.5 \times Q_{S2}, \; \left(R^2 = 1.0, \; p < .0075\right), \tag{13.3}$$

where

Q in units of centimeter per year is annual stream-water yield at the harvested S6 watershed or S2 control watershed

P in units of centimeter is total precipitation during the calendar year

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Expected water yield represents the yield if there was no effect of clearcutting and forest conversion at S6. Change in annual stream-water yield was calculated for each water year by subtracting the predicted from the observed annual yield:

$$\Delta Q_{S6} = Q_{S6\text{-observed}} - Q_{S6\text{-predicted}}, \tag{13.4}$$

A positive $\Delta Q_{S6}$ indicates an increase of stream-water yield relative to the preharvest period. Data from the clearcutting, grazing, and initial conifer growth stage (water years from 1980 to 1989) and conifer growth stages (water years from 1990 to 1999 and 2000 to 2008) were compared to the preharvest stage during water years from 1976 to 1979. Despite the short duration, the calibration period included extremes from the driest year (1976) and a year in the top 10th percentile of wet years (1979). Nonetheless, the statistical power was low given the short precalibration period. The results for the S6 experiment must be considered within this limitation.

During clearcutting, grazing, and the initial years of conifer growth from 1980 to 1989, annual stream-water yield at the S6 watershed increased relative to the S2 control watershed (Figures 13.6 and 13.7). The difference between observed and predicted annual stream-water yield prior to clearcutting ranged from −1% to +1% with a mean difference of 0% ± 1% (Figure 13.6c). During the water year of 1980 when the uplands were clearcut and first grazed, stream-water yield increased by 59% above the amount expected if the uplands had not been clearcut. The largest increase of 78% occurred during 1982, the third and final year of aspen suppression by grazing. The change in annual stream-water yield remained positive until water year 1999 and averaged +39% ± 25% relative to the predicted S6 water yield from 1980 to 1989 (Figure 13.6b). During water years from 1990 to 1999, the mean change in stream-water yield was +17% ± 31%. The mean change in annual stream-water yield from 2000 to 2006 was −28% ± 28% with a maximum change of 69% less yield than expected if the uplands had not been converted to conifers. The recent decrease in annual stream-water yield relative to a mature aspen forest occurred with conifer canopy closure.

The decreased stream-water yield from 2000 to 2006 indicates that the maturing conifer forest yielded less water to the stream than the original aspen forest (Figure 13.7). Prior to clearcutting, stream-water yield was slightly higher at the S2 control watershed than at S6, but the regression slope of S6 on S2 was not different from 1.0 (ANCOVA test, $p > 0.05$). Water yield increased during and after the clearcut and grazing period with no change in slope of the regression of stream-water yield at the S6 and S2 watersheds. When substantial conifer biomass had accrued during the 1990s and conifers began to dominate the overstory, the water yield response changed. Wet years yielded less water during the 1990s and 2000s than wet years prior to the 1990s, as shown by slopes that were different before the 1990s (ANCOVA

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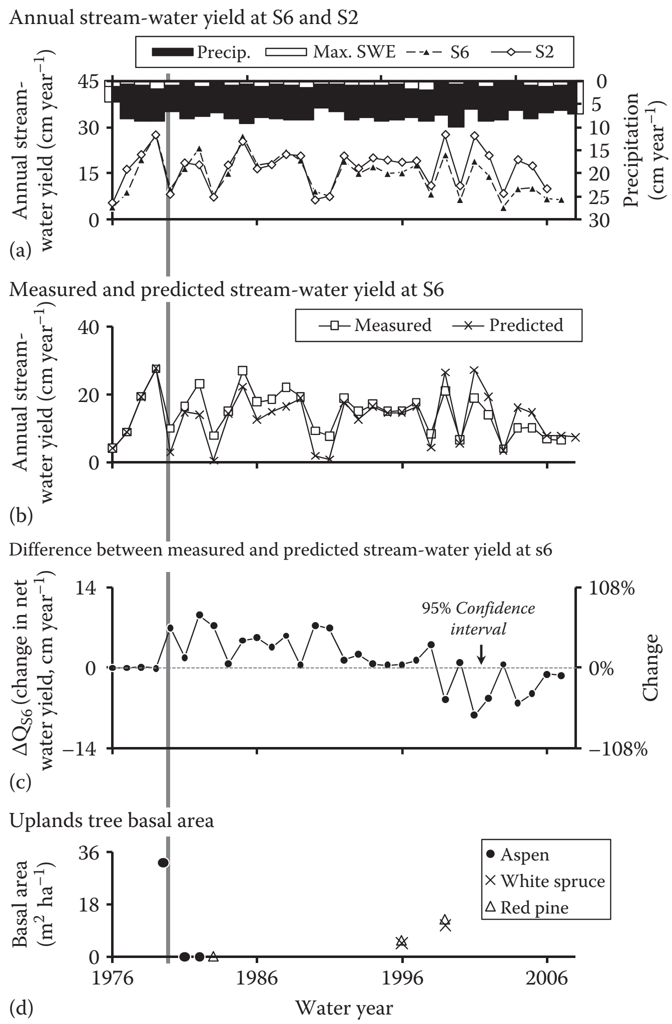


**FIGURE 13.6**
Annual precipitation, maximum SWE, and annual stream-water yield from the S6 and S2 watersheds during each water year (a), measured and regression model predictions of annual streamflow at S6 (b), the difference in water yield between measured and predicted streamflow (c), and uplands tree basal area (d). The shaded line shows the timing of clearcutting during water year 1981.

test, $p < 0.0001$; Figure 13.7). From 2000 to 2006, water yield at S6 decreased even more than in the 1990s.

Streamflow is intermittent at both S2 and S6. Although water yield decreased at S6 during the first decade of the 2000s, the relative number of days per year with streamflow at S6 increased progressively from the preharvest through the postharvest decades as the conifer forest accrued

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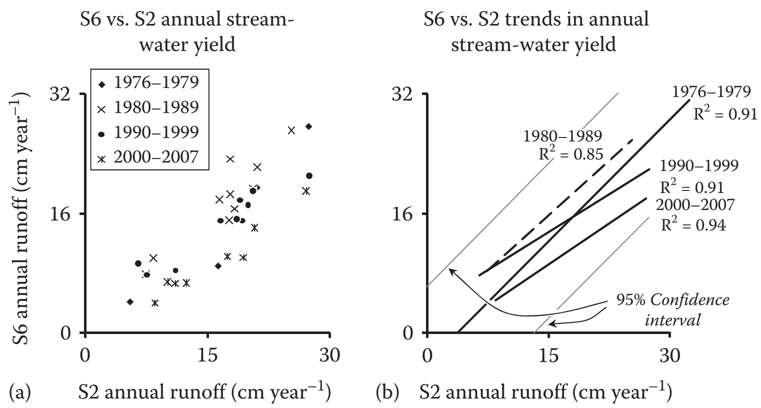


**FIGURE 13.7**
Stream-water yield relationships between the clearcut S6 and the S2 control watersheds. Annual stream-water yield changed in the water years after the uplands aspen harvest (1980–1989) relative to preharvest water years (1976–1979) and decades after conversion to a conifer forest (1990–1999 and 2000–2006). Annual data (a), and trends (b) by response period. To account for wide confidence intervals, high uncertainty, and low statistical power due to the short calibration period at S6 (only 4 years), differences in slope were detected by ANCOVA.

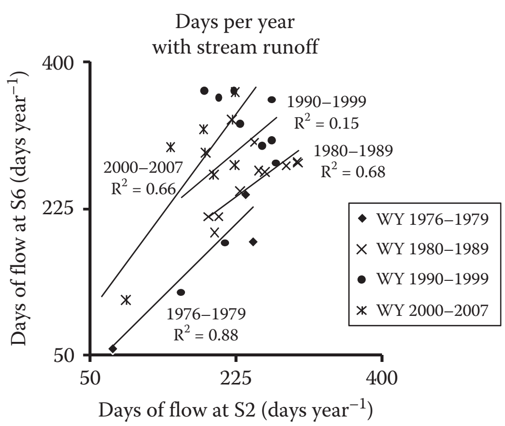


**FIGURE 13.8**
Days per year with streamflow at S6 and S2. The duration of streamflow increased progressively at S6 relative to S2 from the preclearcut stage (1976–1979) through the harvest and grazing (1980s) and conifer afforestation (1990s and 2000s) stages.

biomass (Figure 13.8). Changes to the duration of streamflow at S6 are consistent with increased magnitude of low flow during summer (Figure 13.9). Measurements of sap flux for trees on S2 and S6 were initiated in 2009 to determine whether water use differs between upland conifer and aspen forests.

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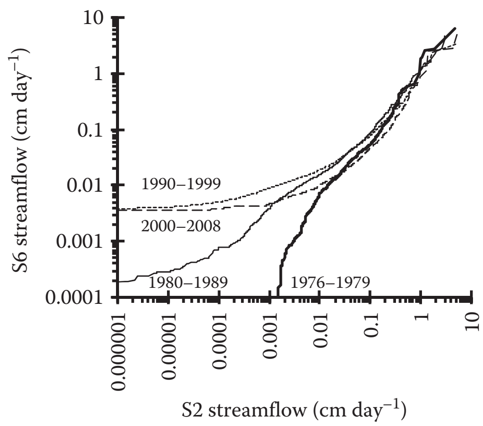


**FIGURE 13.9**
Daily streamflow at S6 versus S2. Low flow increased at S6 during the 1980s after the clearcut into the 1990s and 2000s. The new flow regime stabilized during the 1990s and 2000s.

### *Changes in Peak Flow to Rainfall and Snowmelt*

Peak streamflow responses to both snowmelt and rainfall differed between the S6 and S4 upland clearcut studies. Peak streamflow during snowmelt was higher at the S6 than the S2 watershed before the clearcutting (Figure 13.10a). The snowmelt peak response was similar prior to clearcutting and during water years from 1990 to 1999. During the harvest and grazing stage

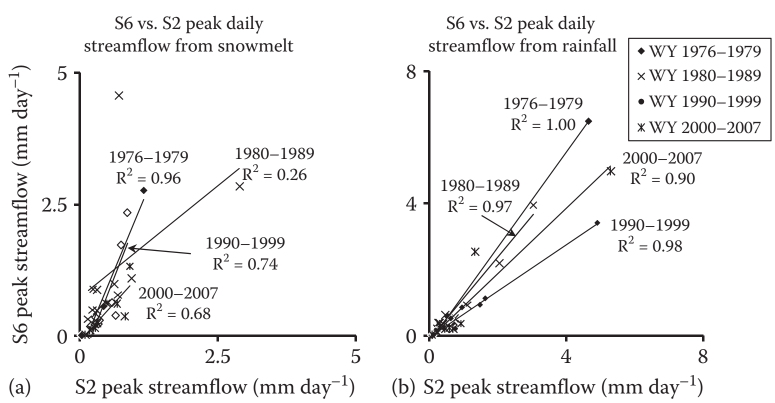


**FIGURE 13.10**
Peak daily stream-water yield from rainfall (a) and snowmelt (b) in each water year, relationships between the clearcut S6 and the S2 control watersheds during the preclearcut (1976–1979), clearcut (1980s), and postclearcut periods (1990s and 2000s).

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(1980–1989) and during water years from 2000 to 2006, the magnitudes of peak flow during snowmelt were about the same at S2 and S6.

Peak streamflow in response to rainfall increased marginally during the decade after clearcutting and progressively decreased during following decades as annual stream-water yield decreased (Figure 13.10b). At S6, peak streamflow response to rainfall during the clearcutting and grazing period decreased relative to the 1976–1979 preclearcutting period (Figure 13.10a). Peak streamflow response decreased further during water years from 1990 to 1999. Peak streamflow response to rainfall increased from the 1990s to the 2000s, but peak streamflow at S6 was still low relative to the preharvest stage.

Interception of rain and snow water by conifer canopies exceeds that of hardwood species (Helvey 1967; Zinke 1967; Verry 1976). Consequently, more intercepted rain may evaporate from conifer canopies, reduce precipitation inputs to upland soils, and reduce lateral subsurface runoff from hillslopes to peatlands. The decreased water yield at the S6 watershed following conversion of uplands to conifers is similar to the results at Coweeta Hydrologic Laboratory in North Carolina where a hardwood forest was converted to eastern white pine (*P. strobus*) and is consistent with increased canopy interception after conversion of hardwoods to conifers (Swank and Douglass 1974; Swank et al. 1988; Hornbeck et al. 1993). Precipitation inputs decrease due to increased interception on conifer canopies and sublimation of snow relative to open areas and leafless hardwood canopies. Transpiration when moisture is not limiting also is higher for conifer than hardwood canopies due largely to leaf area indices that are up to 10 times higher than hardwoods (Kozlowski 1943; Swank et al. 1988). Because most of the annual yield of stream water occurs in response to spring snowmelt, increased losses of winter precipitation with increased interception and sublimation in forests converted to conifers may influence peak streamflow during snowmelt events, which is consistent with the disproportionate decrease of water yield during wetter years, decreased peak streamflow during snowmelt, and a longer duration of streamflow.

### *Changes in Bog Water Levels*

Water levels in the S6 bog increased relative to the S2 bog after the upland clearcutting, grazing, and forest conversion (Figure 13.11). Data on bog water levels are available since 1977. Mean water table elevations and water table fluctuations were similar between the 1977 and 1979 calibration and 1980s postclearcutting periods. In the 1990s and 2000s, mean water level decreased at the S2 control watershed and increased at the S6 watershed. Although not intuitive given the decrease in water yield that occurred over the past two decades, the increased water level was consistent with increased days of low flow and the increased magnitude of low flow relative to the S2 control watershed. The change in boundary layer conditions at a watershed

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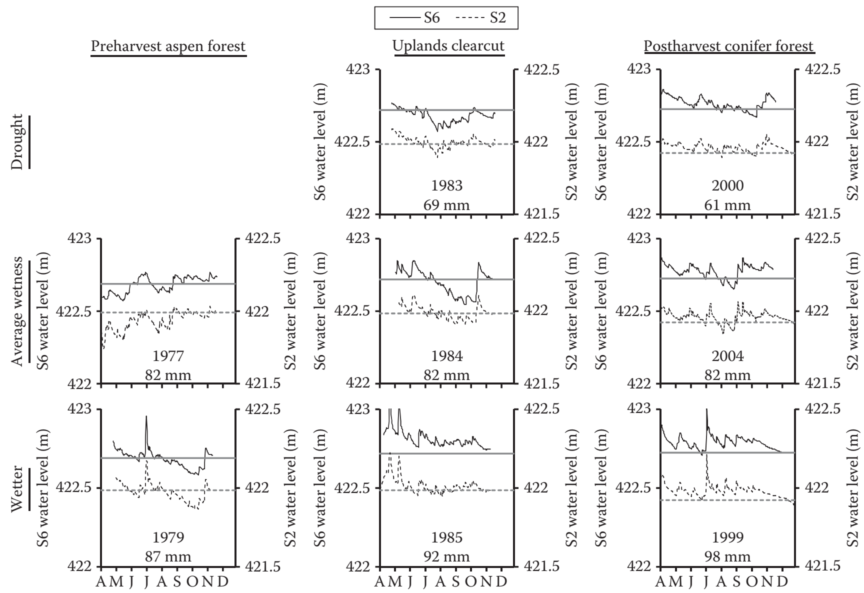


**FIGURE 13.11**
Daily bog water levels in the S6 bog during a year for preharvest aspen, clearcut, and postharvest conifer forest stages shown relative the control S2 watershed. Water levels are shown during drought, average, and above average wetness conditions except for the pretreatment stage when comparable dry conditions did not occur. The precipitation input is shown below the water year. The horizontal lines show the mean bog water level for S6 (solid) and S2 (hashed) during the preharvest water years from 1977 to 1979, during the postharvest water years from 1980 to 1989, and the accruing conifer forest stage (1990s and 2000s).

converted to an upland conifer canopy may also affect vapor fluxes from the bog conifers.

### *Land-Management Implications of the S6 Upland Clearcutting and Forest Conversion Experiment*

The observed decrease in annual streamflow after establishment of a conifer forest on the S6 uplands suggests that annual stream-water yields and streamflow peaks probably were lower before European settlement and widespread forest harvesting during the late 1800s and early 1900s. Pines dominated presettlement northern forests that included mixed hardwoods. Currently, the most widespread forests are primary succession and have deciduous species with few or no conifers in the overstory canopy. Although the S6 conversion to a dense spruce and pine plantation represents an extreme version of a presettlement forest, annual peak streamflow at the 1.5 year recurrence interval would be smaller in magnitude for presettlement forests (Lu 1994).

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## Effects of Upland Forest Harvesting on Streamflow Peaks

The mixed upland/wetland watersheds at the MEF are typical of watersheds throughout the Upper Great Lakes region. Forest harvesting of the uplands increases or reduces stormflow peaks depending on the relative amount of the entire watershed harvested. Figure 13.12 shows the progression of peak-flow change from normal forests more than 15 years of age to watersheds with an increasing percentage of young forests (15 years and less) or open pasture and shrub land (Verry et al. 1983; Verry 2004).

Increases in peak flow for rainstorms are caused by logging on wet soils that compact the soil and reduces infiltration. Increases or reductions in peak flow for snowmelt are caused by the desynchronization of snowmelt in the watershed (Verry 2004). The frequency of the peak flows in Figure 13.13 is unknown, because each data point is based on actual measurements from MEF watershed studies (e.g., Verry et al. 1983), long-term data from the Mississippi and Minnesota river basins (Verry 1986), channel morphology studies in Wisconsin (Fitzpatrick et al. 1999), and from a modeling study at MEF (Lu 1994). Lu examined stormflow frequency by modeling peak-flow response using an 80 year precipitation record that was measured nearby at a meteorological station in Grand Rapids, MN. He found that the magnitude

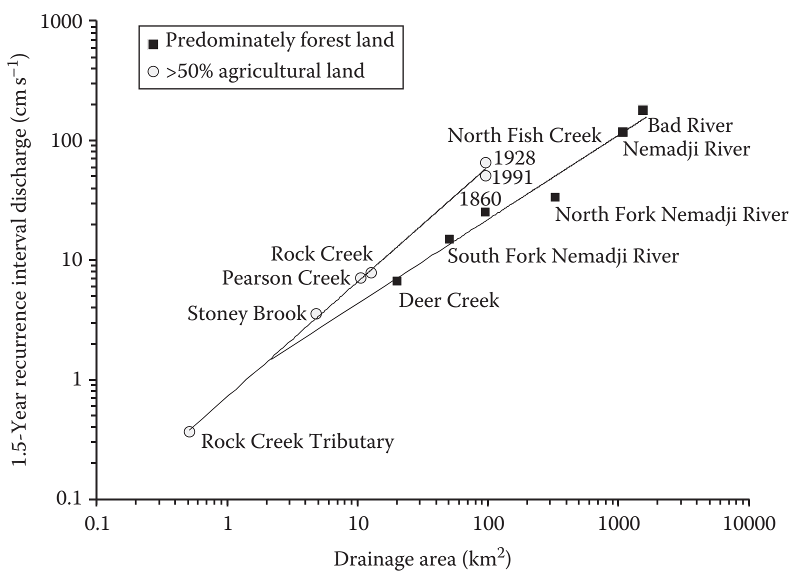


**FIGURE 13.12**
Change in annual peak streamflow from forested watersheds in the Lake States as a percentage of the basin in open or young forests (<16 years old). (Reproduced from Verry, E.S., Land fragmentation and impacts to streams and fish in the central and upper Midwest, in *Lessons for Watershed Research in the Future; A Century of Forest and Wildland Watershed Lessons*, Ice, G.G. and Stednick, J.D. (eds.), Society of American Foresters, Bethesda, MD, pp. 129–154, 2004.)

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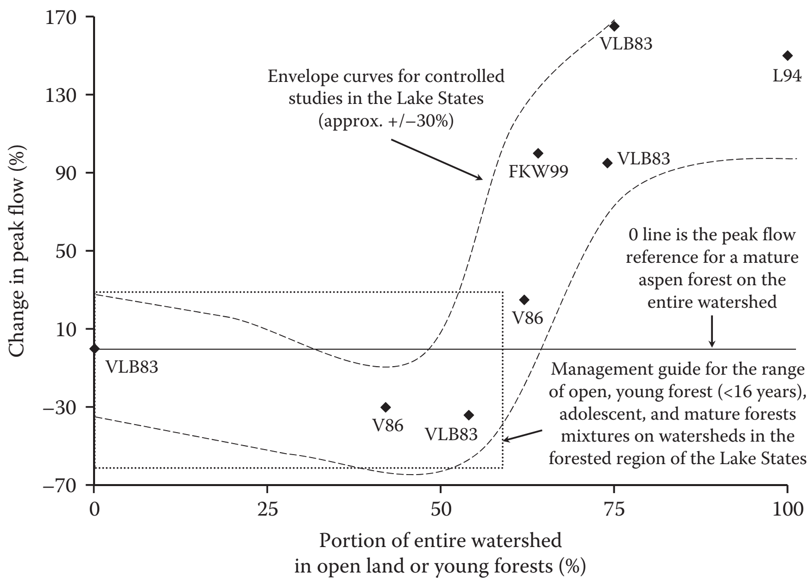


**FIGURE 13.13**
Change in the annual maximum daily snowmelt peak-flow frequency from a mature aspen watershed (solid line) to a recently harvested aspen watershed (dashed line) in Minnesota. Modified from Lu (1994). Lightly dashed lines are 95% confidence intervals. (Reproduced from Verry, E.S., Land fragmentation and impacts to streams and fish in the central and upper Midwest, in: *Lessons for Watershed Research in the Future; A Century of Forest and Wildland Watershed Lessons*, Ice, G.G. and Stednick, J.D. (eds.), Society of American Foresters, Bethesda, MD, pp. 129–154, 2004.)

of storms at a given frequency was increased by upland forest harvesting; storm frequencies ranged from 1 to 30 years (Figure 13.14).

Bankfull or channel-forming flow occurs on average with a 1.5 year frequency (Leopold et al. 1958). That is significant because bankfull flow maintains channel morphology and dimensions. When bankfull flow increases, the channel becomes wider, deeper, or both to accommodate the higher discharge at the 1.5 year frequency. The additional sediment caused by channel scour destabilizes the channel, resulting in a long period of adjustment to new channel dimensions. During this time, fine sediment in the channel can cover gravel used for spawning beds. Changes in bankfull discharge have been documented for clay basins along the south shore of Lake Superior based on long-term streamflow records of the U.S. Geological Survey (Figure 13.14).

The change in bankfull discharge at the MEF was verified with long-term US Geological Survey streamflow data for watersheds along the south shore of Lake Superior in Minnesota and about 200 km east in Wisconsin. In these basins on clay soils, the 1.5 year bankfull peak flow increased about 2.5-fold when predominately forested watersheds were converted to predominately agricultural, "open" lands (Verry 2004).

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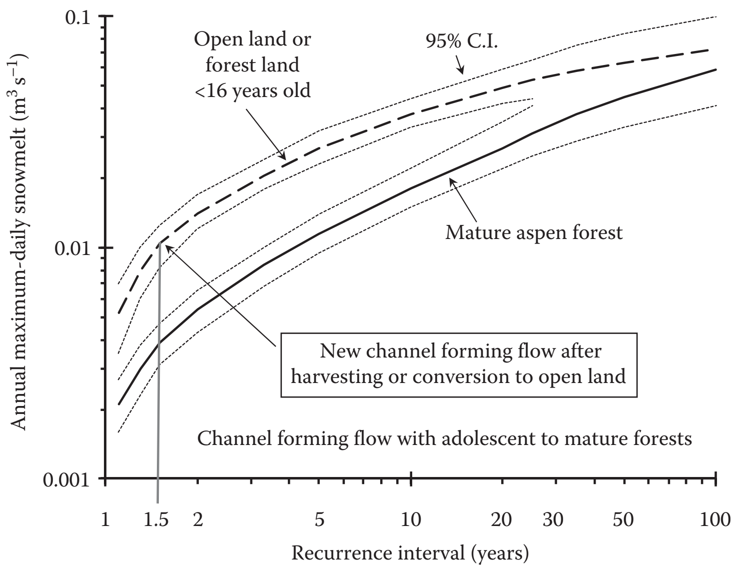


**FIGURE 13.14**
Effects of forest conversion from forests to agriculture for basins in the Southern Lake Superior Clay Belt on bankfull flow (about 1.5 year discharge response). Curves were fit visually. The North Fish Creek data represents a progression from forest cover (1860) to row crop and pasture agriculture in more than half of the basin (1928) to eventually reversion to forests (1991). (Modified from Verry, E.S., Land fragmentation and impacts to streams and fish in the central and upper Midwest, in *Lessons for Watershed Research in the Future; A Century of Forest and Wildland Watershed Lessons*, Ice, G.G. and Stednick, J.D. (eds.), Society of American Foresters, Bethesda, MD, pp. 129–154, 2004 with data on North Fish Creek from Fitzpatrick, F.A. et al., Effects of historical land-cover changes on flooding and sedimentation North Fish Creek, Wisconsin, Water Resources Investigation Report 99-4083, U.S. Geological Survey, U.S. Department of the Interior, Middleton, WI, 1999.)

## Hydrologic Responses to Peatland Harvests

Although less common than harvests of upland forests in the north-central United States, black spruce may be commercially clearcut, stripcut, and patch cut from peatlands (Johnston 1977; Grigal and Brooks 1997). The effects of clearcutting on water yield and water tables could differ in relation to the unique hydrological and hydrochemical settings of bogs and fens. Although water levels in both bogs and fens are drawn down by evaporation and transpiration (Nichols and Brown 1980), the differences are more pronounced in bog watersheds where precipitation is the only source of inflowing water. Fens have a more stable hydrological regime due to connectivity with a regional aquifer and groundwater inputs (Bay 1967). The hydrological differences between fens and bogs may affect the restocking of peatland forests

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after clearcutting. If black spruce is harvested from peatlands, changes to the hydrological setting such as hydroperiod or maximum water levels and loss of a viable seed source from isolated peatlands like those at the MEF could inhibit the regrowth of black spruce.

Clearcutting is more common than stripcutting or patch cutting of black spruce (Grigal and Brooks 1997). Most peatland conifer stands cleared by fire, wind, or large cuts need 20–25 years to reach full stocking. Black spruce seeds remain viable for only 1 year, and seeding or seedling planting may be required to regenerate fully stocked black spruce stands where clearcuts remove the seedstock (Verry and Elling 1978). Strip and patch cuts within the 120 m dispersal distance of black spruce retain seedstock to regenerate fully stocked black spruce forests on clearcut areas. Once seedlings are established in cutover areas, strips and patches of remaining black spruce may be harvested to complete a commercial clearcut.

## Bog Stripcutting and Clearcutting

The peatland in the S1 watershed was strip clearcut in 1969, and the uncut strips were clearcut in 1974 to remove the remaining black spruce. The study was designed to quantify hydrological responses to stripcutting and clearcutting as well as evaluate regeneration of black spruce on the peatland. Verry (1981) published results on the hydrological responses during the first 10 years after stripcutting. In addition, effects on micrometeorology (Brown 1972a,b) and black spruce regeneration (Verry and Elling 1978) have been reported for the S1 study.

Streamflow and bog water levels were measured from 1961 to 1980 at the 33.2 ha S1 watershed (Chapter 2). The 8.1 ha wetland area is surrounded by 25.1 ha of upland hardwood forest. Two aspen stands on the uplands were aged 44 and 52 years old and had a basal area of 22 $m^2$ $ha^{-1}$ prior to black spruce stripcutting. The two black spruce stands on the bog were 62 and 73 years old and had a basal area of 7.0 $m^2$ $ha^{-1}$ (Verry 1969; Brown 1973). Eight 30 m-wide strips of black spruce were cut during January and February 1969 when the bog surface was frozen and snow covered. The strips were cut on a 110° azimuth that was perpendicular to the axis of the peatland. Black spruce was removed from 43% of the peatland surface area or 8% of the entire watershed area (Figure 12.3). Wood was cut, piled, and then hauled from the bog using a crawler tractor and a skidder. The stripcuts were separated by 46 m-wide uncut strips that served as a seed stock for the harvested strips. A narrow strip of black spruce was cut along the eastern margin of the bog to move the timber among the strips to a yarding area in the uplands between the road and the bog. The upland vegetation was not disturbed except for the logging yarding area where trees were stored before being loaded on to trucks. Slash was piled in two rows within each strip to expose most of the bog surface for black spruce seeding from natural dispersal. The strips of black spruce remaining from the 1969 cuts were then clearcut between December 4, 1973

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and January 17, 1974 to complete the commercial harvest. The logging slash from the 1974 cutting was progressively piled and burned (Verry and Elling 1978).

Short- and long-term changes in floristics were found. Increased growth of grasses and sedges was observed during 1970 and 1971. Brown (1973) measured the increased production of sedges and decreased total coverage of shrubs 3 years after the first stripcutting. By 1971, the cut strips were stocked with 4370 black spruce per ha (Verry and Elling 1978). Regrowing seedlings on the first stripcuts were not affected by the 1974 cutting, and stem density exceeded 5400 trees per ha by 1976 (Verry and Elling 1978). However, the second set of strips were understocked with only 1680 trees per ha by 1977. Verry and Elling (1978) concluded that seed stock from uncut strips needed to be available for at least 2 years to naturally regenerate adequately stocked black spruce stands on small isolated peatlands.

Net radiation was measured 1 m above the bog surface in the center of a stripcut and 3 m above the black spruce canopy in an uncut strip during 1969 and 1970 (Brown 1972a). Shortwave radiation was measured about 1 km to the west (Berglund and Mace 1972; Chapter 2). During the first summer after stripcutting, net radiation did not differ between the clearcut strip and adjacent black spruce strips (Brown 1972a). In the second summer, less solar radiation (14% less during June and 20% during September) was absorbed in the clearcut strip than above the black spruce. Brown (1972a) attributed these differences to decreased albedo and decreased conversion of solar radiation to sensible heat in cut strips relative to the intact black spruce canopy in the undisturbed strips. These differences showed that while more energy was available for evapotranspiration above the open bog surface in the stripcuts, more solar energy was converted to sensible heat by black spruce in an uncut strip. During 1970, windspeed was measured with three-cup anemometers that were located with the net radiometers (Brown 1972b). Windspeed and duration increased in the cut strip, which suggested increased evapotranspiration from surface vegetation due to the greater advection of energy and the possibility of enhanced wind-driven water flux (Brown 1972b). Subsurface temperatures at depths of 2.5, 30, 100, and 200 cm did not change in cut strips despite changes of energy fluxes, wind dynamics, and temperatures above the surface (Brown 1976).

### *Changes in Annual Water Yield and Bog Water Tables*

As reported by Verry (1981), water yield did not change when only 8% of the entire watershed was devegetated due to stripcutting during 1969 or when 24% of the total area was free of overstory vegetation after clearcutting during 1974 (Figure 13.15). Despite slight differences, the slopes of the regression relationships between stream-water yields at S1 and S5 are not significantly different during the preharvest, stripcutting, and clearcutting stages.

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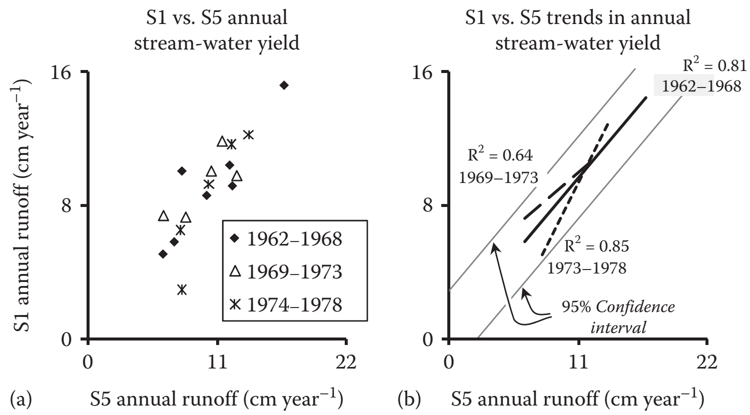


**FIGURE 13.15**
Stream-water yield relationships between the stripcut S1 and the S5 control watersheds. Annual stream-water yield did not change in response after the 1969 strip cut or the 1974 clear-cut that removed the uncut strips of black spruce.

When Verry (1981) first interpreted results after 10 years, he concluded that the amplitude of bog water table fluctuation increased after clearcutting. The maximum annual bog water table elevation appeared to be higher and the minimum lower. Subsequent analysis of the data showed that bog water table responses were similar except during the severe drought of 1976 when the decline in water level at the S1 bog was more pronounced than that at the control bogs in the S5 (Figure 13.16) and S2 watersheds. Although the severe decline in water table at S1 coincided with the postclearcut stage, this pronounced decline was plausibly related more to drought severity and intersite variability, because the berm on the downgradient end of the S1 bog is more permeable than the more well-sealed outlets of the S5 and S2 control watersheds.

### *Forest Management and Hydrological Implications of the S1 Peatland Harvest Experiment*

The ensemble of studies at the S1 watershed show that stream-water yield was not affected by stripcutting or clearcutting and that small isolated peatlands were hydrologically resilient to stripcutting and clearcutting when the uplands were not deforested. Studies at S1 showed changes in floristics (Brown 1973) and differences in evaporation and energy budgets between forested and cut strips (Brown 1972a,b). However, these differences did not affect the annual responses of stream-water yield. In contrast to the clearcutting of upland forests at the S4 and S6 watersheds, effects on annual stream-water yield were not detectable at the S1 watershed after stripcutting or

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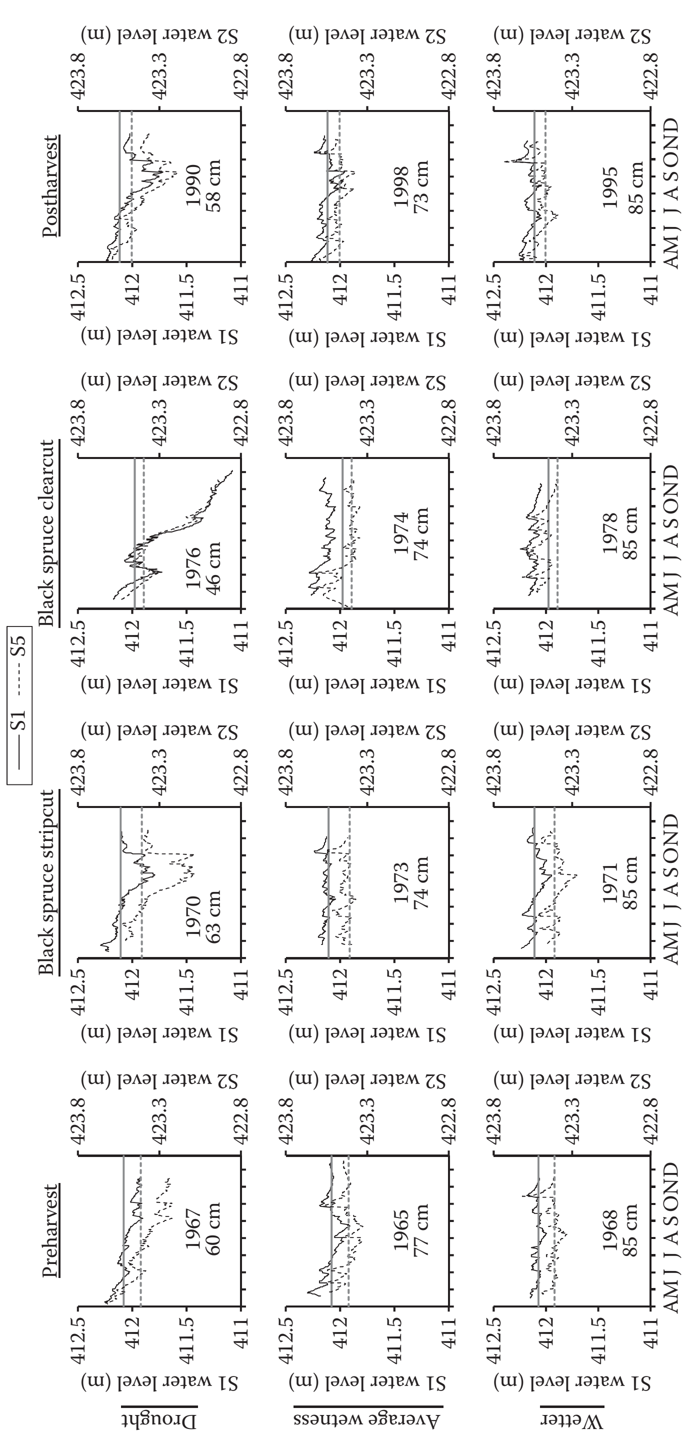


**FIGURE 13.16**
Daily water levels in the S1 bog during a year for preharvest, stripcut, clearcut, and postharvest stages relative the control S2 watershed. Water levels are shown during drought, average, and above average wetness conditions. The annual precipitation input is shown below the water year. The horizontal lines show mean bog water levels for S1 (solid) and S5 (hashed) during the preharvest water years from 1964 to 1968, the post-stripcut period from 1969 to 1973, the post-clearcut period from 1974 to 1978, and the post-harvest period from 1980 to 2008.

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clearcutting. These differences were perhaps related to the small area (24%) that was cleared of black spruce in the S1 bog.

### Fen Clearcut

Trees on the S3 peatland were clearcut to evaluate how the effects of peatland black spruce harvesting differed between bogs and fens. All trees taller than 3 m were cut between December 15, 1972 and January 24, 1973. Merchantable timber was removed with a rubber tired loader, skidder, and tractor. An area of alder was not economical to commercially clearcut, but the alder were cut for research purposes. The fen surface was prepared for planting of black spruce and white cedar seedlings in July1973 using a controlled burn of the slash (Knighton and Stiegler 1981).

Bay (1967, 1968) first described different hydrological responses of the S3 fen watershed relative to perched bog watersheds. Unlike the intermittent flow from the perched bogs, outflow from the S3 watershed is perennial. The size of the S3 watershed, 72 ha, is more than seven times larger than S2. Annual stream-water yield at S3, which averages 6777 ± 3994 cm, is more than two orders of magnitude larger, because annual stream-water yield from the S3 watershed is dominated by water inflow from the regional groundwater system (Bay 1967). Because so much of the S3 outflow water originated from groundwater inputs from beyond the watershed boundaries, effects of clearcutting on water yield were not expected and were not apparent in the paired-watershed data (Figure 13.17). Moreover, fluctuations in water yield and water table elevations at the S3 watershed often decoupled from the responses at the S2 control watershed. In the years following the fen clearcutting, annual stream-water yield increased for three consecutive years at the S2 watershed during which stream-water yield at the S3 watershed decreased for 2 years and then increased. From the late 1970s through the early 2000s, stream-water yield at the S3 watershed increased relative to the previous decades (Figure 13.17c). This increase was likely related to the statewide increase in groundwater levels that accompanied an increasing trend in rainfall during late autumn after the drought of the 1960s. These differences make clear that the S3 fen clearcut was not comparable to the S2 control watershed using the paired-watershed approach.

## Summary

- The findings from paired-watershed studies at the MEF were consistent with a broader range of watershed studies. However, some findings reflect the unique hydrological responses of lowland watersheds with uplands that drain to peatland-fed streams.

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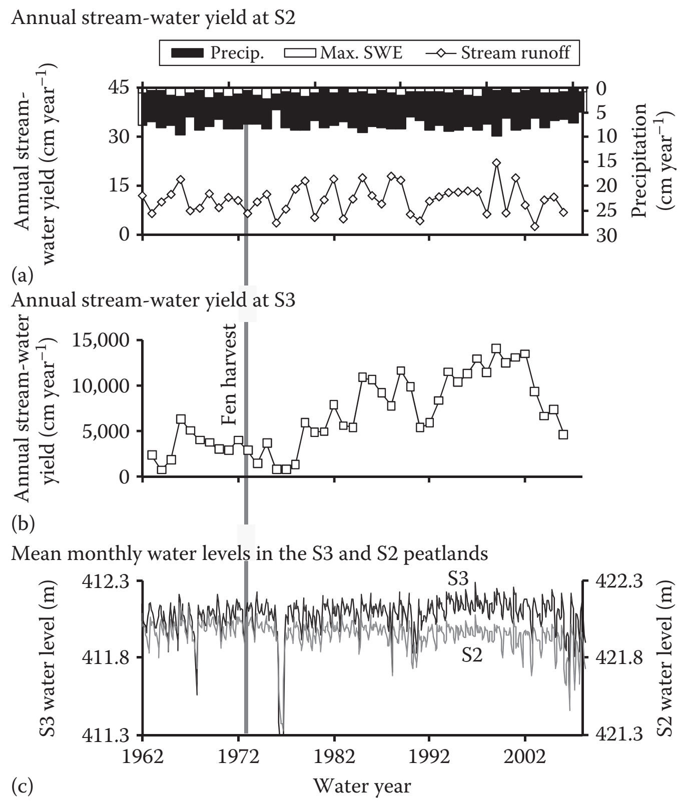


**FIGURE 13.17**
Annual precipitation, maximum SWE, and annual stream-water yield at S2 bog during each water year (a), annual streamflow at the S3 fen (b), and the mean monthly water levels in the S3 and S2 peatlands (c). The shaded vertical line marks the time of the 1963 fen clearcut.

- Annual water yield increased following clearcutting of upland aspen forests. Stream-water yields from watersheds with large central bogs were high for about a decade and then decreased as biomass increased relative to the preharvest stages. Water yields decreased more quickly at the S6 watershed where the aspen forest was converted to conifers. Peak streamflow in response to rainfall and snowmelt differed between the S4 and S6 clearcuts, and responses were consistent with changes in interception and evapotranspiration between aspen and conifer forests. Bog water tables increased transiently in response to both upland clearcuts probably as a result of increased subsurface runoff from surrounding hillslopes into the peatlands when the uplands had no or little tree cover to intercept and evapotranspire precipitation inputs.

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- Stripcutting and clearcutting of black spruce in a bog affected floristics and micrometeorology, but effects on annual water yield and the water table fluctuation dynamics were not detectable, perhaps because of the small portion of the watershed area (24%) that was harvested. When a 37 year-long time series was considered, the magnitude of water table fluctuations did not change in response to bog clearcutting as interpreted originally after 10 years of postharvest data. Interpretation of the shorter data series was confounded by an unexpected water table response due to an extreme drought that occurred 2 years after total clearcutting of the S1 peatland. Our ability to reinterpret initial findings from the clearcut studies illustrates the importance of long-term records.
- The effects of regional groundwater inputs masked the effects of clearcutting, and the paired-watershed approach was not valid for deciphering annual water yield responses at the S3 watershed. Fen groundwater tables vary with regional groundwater aquifer and transboundary groundwater inflow to the S3 watershed that is driven by responses to decadal scale cycles of drought and lags that are associated with the time needed to recharge the spatially extensive aquifer.

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