Chapter 14
Contributions of Studies on Experimental Forests to Hydrology and Watershed Management

Gerald J. Gottfried, Peter F. Ffolliott, Kenneth N. Brooks, Randall K. Kolka, Carol B. Raish and Daniel G. Neary

Abstract The link between healthy forests and watersheds and healthy streamflow and quality water is universally recognized. The major rivers of the USA originate in the forested mountains of the western and eastern USA and the glaciated regions of the Lake States and Great Plains and produce almost two-thirds of the nation's clean water supply. Original logging and mismanagement of upstream forested watersheds often resulted in degradation of land and water resources and adversely impacted aquatic and human populations. During the 30-year period, between the 1930s and 1960s, experimental forests, ranges, and watersheds were established on national forests and adjacent lands to study the impacts of land conditions on water yield, stormflow, water quality, and nutrient cycling. While the impact of sustained timber production was an original research focus, current efforts include research on nutrient cycling, carbon sequestration, climate change, fire effects, and the impacts of insects and diseases. The experimental forest network of long-term meteorological and biological records is invaluable for evaluations of potential climate change and its consequences on the forests and water resources. This chapter reviews hydrology

G. J. Gottfried (✉)
Rocky Mountain Research Station, USDA Forest Service, 2324 East McDowell Rd., Phoenix, AZ 85006-2496, USA
Phone: 602-225-5357
e-mail: ggottfried@fs.fed.us

P. F. Ffolliott
School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, USA

K. N. Brooks
Department of Forest Resources, University of Minnesota, St. Paul, MN, USA

R. K. Kolka
Northern Research Station, USDA Forest Service, 1831 Hwy 169 East, Grand Rapids, MN 55744, USA

C. B. Raish
Rocky Mountain Research Station, USDA Forest Service, 333 Broadway Boulevard Southeast, Albuquerque, NM 87102, USA

D. G. Neary
Rocky Mountain Research Station, USDA Forest Service, 2500 South Pine Knoll Drive, Flagstaff, AZ 86001, USA

D. C. Hayes et al. (eds.), *USDA Forest Service Experimental Forests and Ranges,*
DOI 10.1007/978-1-4614-1818-4_14,

and watershed management research at a sample of experimental forests and areas from throughout the USA. The chapter includes studies conducted in the forests near the Fort Valley Experimental Forest and on the Sierra Ancha Experimental Forest in Arizona, on the Fraser Experimental Forest in Colorado, and the H.J. Andrews Experimental Forest in Oregon. In the East, research at the Coweeta Hydrologic Laboratory in North Carolina, the Hubbard Brook Experimental Forest in New Hampshire, and the Marcell Experimental Forest in Minnesota is reviewed.

Keywords Forest hydrology · Watershed management · Western and eastern experimental forests · Long-term studies and records · Climate change

14.1 Introduction

Forests and rangelands produce almost two-thirds of the nation's clean water supply. The Weeks Act of 1911 acknowledged the important link between forests and watersheds and the protection of navigable rivers. Efforts to ensure quality water and flows that sustain stream and floodplain habitats were a significant reason for the establishment of the National Forest System. A century of research and monitoring in experimental forests and rangelands, largely by the USDA Forest Service, provides a rich body of knowledge and long-term data to guide land management stewardship that preserves the integrity of our water resources (Ice and Stednick 2004).

This chapter reviews research on selected experimental forests in the western and eastern USA to highlight their contributions to forest hydrology and watershed management and the link between good silviculture and good watershed management. Many studies were initiated because of local concerns that forestland management could have an adverse effect on water resources or produce peak stormflows that would negatively impact downstream infrastructures. In the southwestern USA, there were concerns that increased tree densities were causing declines in streamflow volumes. In the Pacific Northwest, concerns centered on large-scale clearcutting in the forested headwaters and the impacts of higher stormflows on water quality, stream habitat, and on endangered or sensitive wildlife species. Impacts of changes in summer streamflows on salmon fisheries were also important concerns in the Pacific Northwest. While timber and water yield augmentation are no longer a paramount concern, the knowledge gained from the early research on experimental forests is vital to current planning and interpretation of multiple resource management. Experimental forests and ranges can play an important part in answering current questions concerning the role, management, and effects of fire. Hydrologic and meteorological records, which are fundamental to watershed experiments, are invaluable for setting baselines to evaluate current and future climate change and new forestland management options. Some records are more than 100 years old. The value of long-term experimental watershed studies and monitoring for addressing future forest water issues has gained considerable attention in the last decade (National Research Council (NRC) 2008; Buttle et al.

2005; Stednick et al. 2004). However, concerns associated with changing demographics and climate, and issues associated with expanding temporal and spatial scales, pose new questions that may not be adequately addressed from past research (NRC 2008). The uncertainty of land use and climate change suggests that a new and expanded forest hydrology research and monitoring program is necessary to support the development of predictive models that complement, but do not replace watershed studies (Stednick et al. 2004). This chapter discusses the importance of continuing monitoring programs in many existing experimental watersheds and an expanded vision of watershed research for the twenty-first century.

14.2 Experimental Watersheds of the West

Watershed studies from four western experimental forests and research watershed areas are considered representative of watershed research in the West. Fort Valley, the oldest experimental forest in the country (Olberding and Moore 2008), does not contain gauged watersheds, but the silvicultural research provides the basis for treatments on the adjacent Beaver Creek watersheds in central Arizona and higher-elevation forests in the Sierra Ancha Experimental Forest, north of Globe, Arizona, and its satellite, Castle Creek, in eastern Arizona. The Fraser Experimental Forest in the Front Range of Colorado emphasizes the link between forest conditions and water in high elevation, snow-dominated watersheds. Finally, the H.J. Andrews Experimental Forest in the Cascade Mountains of Oregon represents watershed research in rain-dominated forests of the Pacific Northwest.

14.2.1 Mixed Conifer and Ponderosa Pine Experimental Program in Arizona

Water has always been a critical issue in the arid Southwest with its periodic cycles of drought and abundant precipitation. Roosevelt Dam, on the Salt River in central Arizona, was completed in 1911 to ensure that the farms and developing cities in the Phoenix Area had adequate water supplies. The Tonto National Forest was established to protect and manage the lake's watershed. Watershed research has been an important part of activities to protect and, where possible, to augment streamflows. The Sierra Ancha Experimental Forest and the Beaver Creek watersheds are centers for watershed studies in mixed conifer and ponderosa pine forests. However, because of the large variety of ecosystem habitats in the Southwest and the need to show that results from the experimental forests were valid in other areas, additional experimental sites were instrumented and treated on adjacent national forestlands (Baker 1999).

14.2.2 Sierra Ancha Experimental Forest

Forest Service watershed research began near Roosevelt Lake in 1925 to ascertain sedimentation rates from the granite soils surrounding the lake. The Parker Creek Experimental Forest was dedicated in 1932 and enlarged in 1938 to form the Sierra Ancha Experimental Forest in the mountains northeast of Roosevelt Lake (Gottfried et al. 1999a). Some of the initial efforts were to gauge several of the creeks to determine the hydrology of streams originating in the higher elevation forests. The three forks of Workman Creek, at 2,075–2,355 m in elevation, that support mixed conifer forests of Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco), white fir (*Abies concolor* var. *concolor (Gord.* and *Glend.*)), and ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelm.) and forests of pure ponderosa pine were part of this effort. Annual precipitation is about 840 mm. One objective at Workman Creek was to study the effects of watershed vegetation on streamflow, erosion, floods, and sedimentation. Treatments were applied to North Fork and South Fork, while Middle Fork was designated as the hydrologic control. The experimental approach used in most watershed studies throughout the USA is based on statistical relationships between paired watersheds (Hewlett 1971). Streamflow or other characteristics from two, and occasionally more, watersheds are compared during a calibration period and then one watershed is treated, while one remains as a hydrological control to account for changing weather from year to year. The pre- and posttreatment relationships are compared to determine if significant differences have occurred.

The first treatments on North Fork were implemented in 1953, and designed to evaluate the impacts of removing vegetation in a series of steps to determine the effects on water yields (Fletcher and Rich 1955). The North Fork treatments were experimental and not designed as potential management options. The first step was to remove riparian trees, mainly Arizona alder (*Alnus oblongifolia* Torr.) and bigtooth maple (*Acer grandidentatum* Nutt.). This treatment, which only covered a small area, did not result in a significant increase in water yields. The second treatment cleared the mixed conifer forest from 32.4 ha and seeded grasses. The third treatment removed the adjacent ponderosa pine forest from 40.5 ha. These two combined treatments resulted in significant water yield increases of 84 % or 69 mm when compared to original conditions (Rich and Gottfried 1976). The increases were still being measured until the weirs were closed in 1983.

The South Fork was harvested according to a standard single-tree selection prescription starting in 1953 (Rich and Gottfried 1976; Gottfried et al. 1999a). A slight but statistically significant increase was detected. The second treatment in 1966 was designed to convert the mixed conifer forest into a ponderosa pine forest and to maintain the stand at 9.2 m^3/ha to optimize both water and tree production. The stocking levels were not achieved and ponderosa pine regeneration efforts were not successful. However, the treatment did result in significant increases in runoff of 111 % or 93 mm with little increase in sedimentation.

Fig. 14.1 Castle Creek East Fork was monitored with 120-degree v-notch weir. The objective on the two Castle Creek watersheds was to start management of the ponderosa pine forest to a system using a 120-year rotation with 20-year cutting cycles. East Fork was the original control watershed but a preharvest watershed prescribed fire treatment was evaluated after 1981. (Photo by G. Gottfried)

The Workman Creek studies indicated that removal of forest vegetation in significant areas and amounts could increase runoff (Rich and Gottfried 1976). They suggested that even-aged management could enhance both tree and water resources and that a system of patch clearcuts scheduled at 20-year intervals over a 120-year rotation could meet these criteria. Current silvicultural prescriptions favor uneven-aged management although small group selection is a component of many prescriptions.

The three watersheds burned in the Coon Creek Wildfire in April 2000. The Middle Fork, with its uncut, old-growth forest suffered high-severity fire damage, the South Fork suffered moderate-severity fire damage, and North Fork had low-severity damage. Postfire runoff and sedimentation are being monitored to determine the hydrologic effects related to different fire severities (Neary et al. 2006).

14.2.3 Castle Creek Timber Harvesting and Thinning Tree Overstories

The two Castle Creek watersheds were established in the White Mountains of eastern Arizona, to study the effects of commercial timber harvesting on streamflow regimes (Fig. 14.1). The watersheds were an extension of the research results from Workman Creek to evaluate the impacts of scattered small patch clearcut openings and harvesting of adjacent trees on water yields (Gottfried et al. 1999b). The Castle Creek watersheds are between 2,380 and 2,620 m in elevation. L. R. Rich, who was based at the Forest Hydrology Laboratory in Tempe, AZ, was instrumental in establishing the Castle Creek watershed experiment.

A silvicultural treatment was applied to the 364-ha West Fork watershed at Castle Creek in 1965–1967 to obtain timber products and place the remaining tree overstory into the “best growing condition possible” by starting the transition from an uneven-aged to an even-aged stand condition (Rich and Thompson 1974). Timber was cleared from one-sixth of the watershed in small openings fitted to the existing stands. The remaining five-sixths were thinned to a basal area of 13.7 m^2/ha to initiate a shelterwood system of "commercial timber management" over a 120-year rotation using a 20-year cutting cycle based on studies at Fort Valley (Schubert 1974). About 50 % of the original basal area of 31 m^2/ha was removed by the harvesting and thinning treatment.

Increases in streamflow remained stable at 13 mm or about 30 %, for more than 20 years after treatment, with these streamflow increases attributed to increased snowpack accumulations and reduced evapotranspiration (ET) rates (Gottfried et al. 1999b). More specifically, the increase in streamflow was presumed to be a result of increased snowpacks in openings because of aerodynamic conditions created by the surrounding mature trees and because of lower transpiration by the new trees in the openings.

The treatment achieved its purpose of initiating a schedule of timber harvesting and management of ponderosa pine in a shelterwood system (Gottfried et al. 1999b). Silvicultural studies at Fort Valley and elsewhere in the region suggested that an even-aged stand structure has a greater "timber-production potential" than an unbalanced stand (Schubert 1974). However, because timber production is no longer a management emphasis in the region, the management focus has shifted to obtaining ecosystem-based, multiple-use benefits. This shift reflects the increasing environmental concerns of the 1960s and 1970s, many of which focused on logging and USDA Forest Service timber management programs. In 1972, the agency produced an action plan, National Forests in a Quality Environment (USDA Forest Service 1972), in response to the National Environmental Policy Act. The plan discussed a variety of issues including problems with logging practices, such as clearcutting. Additional research coming out of this effort recommended increased efforts in multiple-resource management, understanding human interactions with the forest environment, and developing timber management programs that enhance or have minimal environmental impact and are compatible with other uses (Steen 1998). The research at Beaver Creek and Castle Creek anticipated the shift in emphasis as indicated by the bibliography prepared by Baker and Ffolliott (1998) listing research articles covering the entire range of forest resource values.

14.2.4 Prescribed Fire and Watershed Values

In the 1980s, land managers were becoming more concerned about the dangers of large, devastating wildfires. Prescribed fire treatments had not been attempted in forests at that time, although fire had been used in chaparral communities (DeBano et al. 1999, 1998). More recent efforts have evaluated prescribed burning with and without thinning in forest environments. Dieterich (1983) of the Rocky Mountain Research Station suggested that a prescribed burn on an area scheduled for harvesting would reduce the possibilities of a wildfire and increase streamflow because of the reduced forest floor depths and stand densities. Castle Creek was selected for the experiment. The results from the original treatments were stable, and it was decided to reverse the watersheds and treat East Fork and hold the previously treated West Fork as the control. The burn was ignited in November 1981, but only covered 43% of East Fork, mostly adjacent to the main channel (Gottfried and DeBano 1988). Surface fuels were removed, middle forest floor layers were slightly charred, and tree reductions were minor. The burn resulted in a slight but statistically non-significant increase in runoff of 8% or 8 mm. Some significant changes occurred in nutrient concentrations, but the changes were very small and of little consequence in terms of site productivity or water quality.

14.2.5 The Beaver Creek Watersheds

Much of the forest watershed research in the West was initiated in the 1950s because of concerns that increasing forest and woodland stand densities were resulting in declines in surface runoff for local and downstream users during a severe drought period. Results from the watershed experiments influenced forest management into the mid-1980s. The long history of silvicultural studies conducted at Fort Valley, located 17 km northwest of Flagstaff, AZ, provided a basis for testing clearcutting and thinning treatments in ponderosa pine forests on Beaver Creek (Gottfried et al. 2008). Management of ponderosa pine forests in the region has changed since the Beaver Creek and Sierra Ancha treatments were initiated from a timber production emphasis to a more holistic, ecosystem-based perspective. While the importance of land management for water yield augmentation also declined as management for other ecosystem services increased, it remains an important consideration. The interest in managing forests to improve water yields and to regulate snowmelt timing may again become important as the West's population continues to grow.

The 20 Beaver Creek watersheds were established 83 km south of Flagstaff to investigate the potential for increasing streamflow from ponderosa pine forests and pinyon-juniper woodlands in central Arizona (Brown et al. 1974). The watersheds are within the Coconino National Forest and located between 1,980 and 2,440 m in elevation. The Beaver Creek watersheds were established as a result of a meeting of ranchers, the Salt River Valley Water Users Association, which provides water to much of the Phoenix Metropolitan Area, and the Forest Service. Participants were concerned that the dense forests and woodlands were reducing streamflows during a period of extended drought. Watershed management research, which began in 1960, evolved into the evaluation of multiple resources. Impacts of silvicultural treatments on herbage production for livestock and wildlife habitats were important aspects in all watershed studies. Economic models were developed based on research findings. The Beaver Creek watersheds were not formally designated as an experimental forest; however, treatments were implemented cooperatively by personnel from the Coconino National Forest and scientists from Rocky Mountain Forest and Range Experiment Station. H. Brown and D. Worley were the first project leaders, and key scientists included M. Baker, Jr, W. Clary, P. Ffolliott, F. Larson,

Fig. 14.2 The clearcut watershed will not produce ponderosa pine crops for a long time, but treatment has resulted in increases in forage production for livestock; it is valuable as wildlife habitat, and the clearing created a more diverse landscape by breaking up the continuous forest cover. The watershed is also becoming a source for firewood for neighboring communities. (Photo by P. Ffolliott)

and J. Rodgers. The Beaver Creek watersheds are a biosphere reserve in UNESCO's Man and the Biosphere Program. They provide a valuable outdoor classroom and laboratory for university students and visiting scientists.

14.2.5.1 Complete Clearcutting of Tree Overstories

Silvicultural options to meet hydrology and watershed management goals include complete or partial clearcutting tree overstories, thinning tree stands, or combinations of these options. One of the first objectives was to determine the maximum potential of increasing runoff from ponderosa pine forests. The tree overstory of ponderosa pine and intermingling Gambel oak (*Quercus gambelii* Nutt.) and alligator juniper (*Juniperus deppeana* Steud.) on a 172-ha watershed was completely clearcut in 1966–1967 to evaluate the effects of this "most drastic" treatment on streamflow (Fig. 14.2). Merchantable trees were felled and removed from the watershed, and smaller trees and slash were piled in windrows aligned perpendicular to the stream to facilitate transport of overland flow into the channel. The clearcut harvest was not intended as a possible land management treatment.

Streamflow increases for 7 years following the treatment averaged 43 mm or about a 30 % increase. This increase was caused by reductions in tree transpiration and more overland flow from melting snowpacks, the primary source of annual streamflow from the watershed (Baker and Ffolliott 1999). Windrowed slash trapped snow and delayed melting on the lee sides of the windrows until the ambient temperature rose, resulting in more of the overland flow reaching the stream channels. Vegetation and the transpiration rates recovered sufficiently within 7 years for the soil-water depletion to be the same as under the original forest.

The treatment removed the watershed from commercial timber production. Stocking of ponderosa pine reproduction declined from 65 to 15 % after the clearing and remained constant for the following 23 years (Ffolliott and Gottfried 1991).

Fig. 14.3 Heavy thinning was applied to this watershed reducing the basal area to 5.7 m^2/ha. The treatment resulted in significant increases in water yields, but it is unlikely that timber production can be sustained. Forage production and wildlife habitat conditions have improved. (Photo by P. Ffolliott)

It is unlikely that the watershed can be managed for future timber production without site preparation and artificial regeneration. However, research at Fort Valley showed that artificial regeneration must be initiated soon after clearcutting to minimize problems with competing vegetation (Schubert 1974). Management goals other than "commercial timber production" included increases in forage production for livestock grazing and abundant posttreatment oak sprouts, which are beneficial to indigenous ungulates, and firewood for local consumption. The clearing created a more diverse landscape by breaking up the continuous ponderosa pine forest cover.

14.2.5.2 Thinning Tree Stands

A subsequent study at Beaver Creek evaluated the impacts of thinning trees on water production. The ponderosa pine overstory on a 121-ha watershed was commercially harvested by group selection and the residual trees uniformly thinned in 1969 (Fig. 14.3), leaving stands in even-aged groups at a basal area level of about 5.7 m^2/ha. The prescribed basal area level, while relatively low, was above the level where windthrow of ponderosa pine trees occurs. Seventy-five percent of the original basal area was removed. Slash was piled perpendicular to the stream channel (similar to the clearcut treatment).

Increased streamflow following the thinning treatment persisted for 10 years and averaged 41 mm annually—ranging from 10 to 30 % above the predicted streamflow if the watershed had not been treated (Baker and Ffolliott 1999). The streamflow response was attributed to reduced transpiration losses and increased efficiency of winter overland flow to stream channels because of the influence of the windrowed slash.

Stocking of regeneration was reduced from over 50 % before thinning to 2 % after treatment. However, nearly 40 % of the watershed became restocked with natural regeneration within 10 years of the treatment (Ffolliott et al. 2000). It is unlikely that timber production will be sustained, but managing for other resources is possible. Heavy thinning and slash treatments could influence fire behavior and fuel management in the wildland–urbaninterface.

14.2.5.3 Partial Clearcutting and Thinning Tree Overstories

A combination of thinning and clearing trees in strips was carried out on a 546-ha watershed on Beaver Creek in 1970–1971 (Ffolliott and Baker 2001). Trees were cleared in irregularly shaped strips 18 m wide with intervening leave strips 36 m wide. The harvested strips were oriented downslope for more efficient overland flow of water. Ponderosa pine in the leave strips were thinned to 18.4 m^2/ha. The treatment removed 40 % of the basal area on the watershed. Slash was piled in the center of the stripcuts and burned.

The hypothesis was that streamflow increases would occur following treatment because of increased efficiency in transporting overland flow to the stream channel due to the uphill–downhill orientation of the stripcuts and decreased transpiration. Annual streamflow increased 25 mm, but the increase only lasted 4 years (Baker and Ffolliott 1999) because of the rapid recovery of vegetation in the cut strips.

The treatment removed most of the trees in the cut strips and left a mosaic of even-aged tree stands, mostly of trees 20–46 cm in diameter at breast height (d.b.h.) in the intervening leave strips. Stocking of trees in the leave strips increased in the 25-year posttreatment evaluation period (Ffolliott and Baker 2001). Stocking of ponderosa pine seedlings on the watershed declined after treatment and did not fully recover during the subsequent 25 years.

Research results based on existing data or computer simulation models continue to be published providing land and water managers with new knowledge and tools. More information about Beaver Creek and Castle Creek, including a searchable bibliography, can be found at a Rocky Mountain Research Station website: http://www.fs.fed.us/rm/boise/AWAE/labs/awae_flagstaff/watersheds/ and information about Sierra Ancha is presently available at http://www.fs.fed.us/rm/boise/AWAE/labs/awae_flagstaff/Hot_Topics/SierraAnchaExperimentalForest.html. Current research efforts at Sierra Ancha continue to monitor the impacts of the Coon Creek Fire. Although the Beaver Creek installations were closed in the mid-1980s, some of the watersheds have been re-instrumented to study a variety of forestry and ecological questions including the effects of forest restoration treatments, prescribed fire effects, evaluations of ponderosa pine growing stock levels, tree ecophysiology, and long-term climate change.

14.2.6 Fraser Experimental Forest

The Fraser Experimental Forest is situated in the Central Rocky Mountains about 105 km northwest of Denver. Its location is suited for investigations of water yields in high-elevation, snow-dominated forest areas (Alexander and Watkins 1977). Three-fourths of the subalpine forests of lodgepole pine (*Pinus contorta* Dougl. ex Loud.), Engelmann spruce (*Picea engelmannii* Parry), subalpine fir forest (*Abies lasiocarpa* (Hook.) Nutt.), Douglas-fir (*Pseudotsuga menziesii* var.*glauca*), and aspen (*Populus tremuloides* Michx.) are within the "snow zone," above 3,100 m. Snowpack dynamics, therefore, have been studied since the establishment of the experimental forest. Observations were made in natural stands initially to determine how forest types and canopy patterns affect snowpack accumulation. Plot studies of timber harvesting and thinning with measurements of snow accumulation, melt rates, and ET changes came next. The final step in this sequence of research applied timber harvesting and thinning combinations to whole watersheds and measured the effects on streamflow.

14.2.6.1 Plot Studies

Plot studies in mature lodgepole pine provided initial information on how management affected the water cycle, primarily the snow component. The first plots were harvested in 1940 after initial snowpack measurements, with the cuttings ranging from a complete (commercial) clearcut of all trees to partial cuttings retaining a specified reserve of timber volumes (Leaf 1975). An unharvested natural area was retained for comparison. Initial studies determined how different methods and intensities of cutting affected snowpack accumulation and tree reproduction, growth, and mortality. The greatest snowpack accumulation was observed in clearcut plots. Lesser snow accumulations occurred in plots with intermediate cuttings, and the least accumulations occurred in the unharvested natural stands. Differences in snowpack accumulations were caused by the elimination of sublimation from snow intercepted by tree crowns. Sublimation from tree crowns was greater than sublimation from snowpacks in the cut openings where shade and wind were less than on the tree crowns.

14.2.6.2 Watershed Studies

Partial Clearcutting

Results from the plot study were tested at the watershed level on the Fool Creek Watersheds at the Fraser Experimental Forest in stands of lodgepole pine, Engelmann spruce, and subalpine fir. Forty percent of the 289-ha watershed was partially cut in 1954–1956 leaving alternating cut and leave strips varying from 20 m to nearly 121 m wide and 151–182 m long. Cut strips were oriented perpendicular to the contour and changes in streamflow, other hydrologic variables and the residual tree overstory conditions were measured. No cutting was allowed within 27 m of the stream to minimize direct damage to the channel. Logging slash was lopped and scattered. Fifty percent of the merchantable timber was removed from the watershed area. Snow courses were established to study the effects of the treatment on snow accumulation patterns.

Average annual streamflow increased 81 mm or nearly 40 % in the first 28 years following treatment. This increase was attributed largely to an average annual increase in snowpack water equivalent of about 10 % because of reduced interception and sublimation of snow and increases in soil storage (Troendle and King 1985). However, the increase in streamflow has been declining along with decreasing snowpack water equivalents. The streamflow increase 50 years after the treatment averages 58 mm or about 30 % (Elder et al. (2006) in preparation). As vegetation continues to regrow, ET losses will increase, resulting in the diminishing increased streamflow. However, analysis of streamflow records since treatment suggests that treatment effects might last 70 years (Stednick and Troendle 2004).

Sufficient advanced regeneration (seedlings and saplings) survived the treatment to restock all clearcut strips, with greater stocking levels on the wider strips. The number of seeds dispersed from standing trees into the cleared strips in the initial 10 years following treatment was greater in years with the heaviest seed production (Alexander and Watkins 1977). Windfall of trees adjacent to the strips was the major cause of mortality in this period, with about two-thirds of the mortality occurring in the first 2 posttreatment years. According to Elder et al. (2006), there was “adequate regeneration” and “conservative growth” of lodgepole pine 50 years after treatment, while Engelmann spruce exhibited “poor” regeneration and growth. Current constraints on reducing the cover of subalpine forests to increase streamflow include environmental concerns about sustaining commercial timber production practices, providing wildlife habitats, and maintaining outdoor recreational opportunities.

Patch and Shelterwood Cuttings

Effects of silvicultural cuttings on streamflow volumes were subsequently tested on Deadhorse Creek, a 270-ha watershed within the Fraser Experimental Forest that supported spruce-fir along stream bottoms and northern and upper slopes, lodgepole pine on lower and middle-southern slopes, and alpine vegetation above timberline. Patch and shelterwood cutting prescriptions were initiated on Deadhorse Creek based on guidelines from earlier studies on Fraser and elsewhere in the region (Alexander 1969, 1971, 1973; Noble and Ronco 1978; and others). Twelve circular clearcuts of 5H (i.e., 5 tree heights) in diameter—each about 1.2 ha—were cut on the 40-ha North Fork of Deadhorse Creek in 1977–1978 to investigate harvest effects on snow accumulation and resultant streamflow. Trees were harvested on approximately one-third of the watershed in this treatment, which represented an initial effort at creating a stand that could sustain timber management. In a second treatment on Deadhorse Creek, 40 % of the original forest basal area on the 40-ha North Slope was uniformly removed in the first of a three-step shelterwood cutting in 1980–1981. A third treatment on Deadhorse Creek affected about 25 % of the

78-ha Upper Basin, which was harvested in irregularly shaped clearcut openings varying from 1 to 10 ha in size in 1983–1984.

Changes in streamflow regimes following the treatments on Deadhorse Creek have been summarized by Troendle and Kaufmann (1987), Troendle and King (1985), and others. An average annual increase of 61 mm (30 %) in streamflow was observed on North Fork in the first 7 posttreatment years. These yearly increases were correlated with snowpack water equivalents; wetter years had larger increases than drier years. Streamflow response to the treatment on the ungaged North Slope was estimated from the differences between the gaged streamflow on the main stem of Deadhorse Creek and that from the streamflow from the North Fork and Upper Basin. Although partitioning of streamflow in this way decreases the reliability of analyzing the effects of the treatment on this watershed, an analysis of covariance showed no significant increase in streamflow in the first 3 years after the North Slope treatment. Increases in streamflow following treatment on the Upper Basin have occurred only periodically. Clearcuts on this part of the watershed were apparently not as "effective" as those on the North Fork in increasing snowpack accumulation, and consequentially, streamflow. While streamflow significantly increased over the initial evaluation period, covariance analysis indicated that changes in streamflow were not detectable in drier years.

Silvicultural impacts of the timber harvesting and silvicultural practices implemented on Deadhorse Creek—and the Fraser Experimental Forest generally—have been mostly consistent with those expected in subalpine forests. Partial clearcutting in strips or patches (circular openings) and thinning to initiate a shelterwood system of management represent viable and appropriate silvicultural options. Studies at Fraser and in the region have provided guidelines to prescribe reproduction methods for lodgepole pine, Engelmann spruce, and subalpine fir relative to stand structure, windthrow risks, and management goals (Smith 1987). Furthermore, simulation techniques to estimate stand growth and volumes are also available (Alexander and Edminster 1980, 1981) to evaluate management alternatives in these forests. Current research at Fraser is concerned with linkages between forests, riparian areas, and streams to understand nutrient cycling, carbon storage, and snow hydrology. More than 30 studies currently are in progress in addition to long-term monitoring efforts. Such studies demonstrate a changing research focus favoring topics described by Steen (1998) as environmentally sensitive. As always, they are also responsive to current issues of concern. Ecologically based forest management was mandated in a range of legislation including the Clean Water Act of 1972, the Endangered Species Act of 1973, and the National Forest Management Act of 1976, with its mandate to sustain both biological diversity and soil productivity. As a result of these legislative mandates, the USDA Forest Service has shifted the way it manages the land, moving away from operating along functional lines toward an ecosystem management mode of operation (Steen 1998).

Additional information about the Fraser Experimental Forest, including a partial list of publications, can be found at a Rocky Mountain Research Station website: http://www.fs.usda.gov/efr/fraser/.

14.2.7 H.J. Andrews Experimental Forest

H.J. Andrews Experimental Forest is located on the western slope of the Cascade Mountains of Oregon about 80 km east of Eugene. It is administered jointly by the USDA Forest Service's Pacific Northwest Research Station, Oregon State University, and the Willamette National Forest. The experimental forest, which was originally designated as the Blue River Experimental Forest, was renamed in 1953 to honor H. J. Andrews, a past regional forester, who was instrumental in establishing the research area. The climate on the experimental forest is influenced by the Pacific Ocean and is characterized by wet winters and dry summers (Rothacher 1970). Average annual precipitation is about 2,286 mm mostly occurring as rain, except at the highest elevations. Approximately 56–63 % of the annual precipitation runs off as streamflow (Harr 1976). Before timber cutting began in 1950, about two-thirds of the Experimental Forest was cloaked with old-growth forests comprised mainly of 450-year-old Douglas-fir, with the remainder largely in stands that regenerated following wildfires in the mid-1800s. Upper elevations of the Experimental Forest support noble fir (*Abies procera* Rehd.), Pacific silver fir (*Abies amabilis* Dougl. ex Forbes), Douglas-fir, (*Pseudotsuga menziesii* (Mirb) Franco var. *menziesii*), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), while lower elevations are dominated by Douglas-fir, western hemlock, and western redcedar (*Thuja plicata* Donn ex D.Don). Ongoing research projects include experimental watersheds to study the effects of alternative logging systems and road construction on streamflow regimes, sedimentation and nutrient cycling, and the development of posttreatment vegetation and biological diversity. Early concerns focused on how widespread clearcutting in headwater forested watersheds might impact flooding, downstream roads, and developments.

The H.J. Andrews Experimental Forest is a component of the National Science Foundation's Long-Term Ecological Research (LTER) Program. It is also a Biosphere Reserve in UNESCO's Man and the Biosphere Program.

14.2.7.1 Watershed Studies in Old-Growth Forests

H.J. Andrews contains three instrumented watersheds in dense stands of 450-year old-growth Douglas-fir forest (Rothacher 1970) and three in 130-year second-growth Douglas-fir stands (Harr et al. 1982). The watersheds occur on steep, northwest-facing topography. The first study in the old-growth stands evaluated complete clearcutting, a common practice in the forests of the Pacific Northwest, using a skyline system on a 96-ha watershed. Roads were not constructed in this watershed. Slash was broadcast burned. The treatment on the second watershed, approximately 101 ha in size, followed a patch-cutting prescription and included a full road system. A third watershed of about 61 ha was reserved as the hydrologic control.

The initial streamflow increases in the clearcut watershed were roughly proportionate to the area harvested (Rothacher 1970). Statistically significant increases did not occur until 40 % of the watershed was cleared, however. Water yields in 1966 and 1967 (the first 2 years after harvest), which were representative of average climatic conditions, were between 259 and 457 mm greater than the amount that would have been expected prior to treatment.

Approximately 8 % of the patch-cut watershed was cleared during road construction prior to the harvesting operation (Rothacher 1970). Logging began 34 months later, in 1962 and 1963, and cleared an additional 22 % of the watershed in three clearcut units. Slash was burned. Statistical analyses did not indicate a significant difference in streamflow related to road construction. Although greater yields of 170 mm were measured after 25–30 % of the watershed was cleared, the differences were not significant. Two major storms occurred after harvesting that resulted in major stream channel scouring.

The results from the two treatments indicate that streamflow responses are proportional to the reduction in forest cover. Increases are related to declines in ET of the new herbaceous and tree cover relative to the old-growth forest. Streamflow increases should decline in the future as the replacement forest stand develops and transpires more water. Eighty percent of the increases occurred during the wet October–March season. However, summer increases were proportionally greater and possibly more important to downstream users. Rothacher (1970) points out that large streamflow increases on headwater watersheds may not be detectable within the larger watersheds.

Low streamflows in August have implications for regional important salmonid fisheries because it affects the availability of rearing habitats and levels of competition with other species. There are also issues related to water temperatures and oxygen depletion (Hicks et al. 1991). These authors examined the long-term effects of logging the old-growth watersheds on low summer (August) streamflows. Annual streamflows increased on the clearcut watershed relative to the control watershed for the first 8 years following harvesting, but significant increases declined in the subsequent 10 years. Water yield increases for August were eliminated within 3 years of treatment because of vegetation recovery; however, annual water yields remained higher than predicted throughout the study period.

Summer streamflow increased from the patch-cut watershed and remained higher than expected for the 1963–1978 posttreatment period. However, summer and annual water yields from the 1979–1988 posttreatment period were not significantly different from the preharvesting period. The difference between the longevity of increased summer streamflows between the two treated areas was related to the nature of the riparian vegetation along the respective creeks. The riparian corridor in the clearcut area had a vigorous stand of mainly red alder (*Alnus rubra* Bong.). The riparian stand development was related to relatively flat geomorphology along the creek, while the patch-cut area, with a narrow steep valley, did not have a similar well-developed zone (Hicks et al. 1991). The authors assume that the influence of the riparian zone on the decline in summer runoff will be less as conifers begin to dominate the sites and the shade-intolerant broadleaved species become less vigorous.

14.2.7.2 Watershed Studies in Second-Growth Forests

In the second-growth stand, one watershed was clearcut, one harvested according to a shelterwood prescription, and the third was maintained as a control (Harr et al. 1982). The clearcut area contained 383 trees/ha and the shelterwood area contained 334 trees/ha prior to harvesting. High-lead cable logging, where logs are suspended above the ground during skidding operations, was used for 90 % of the clearcutting operation. The watershed was planted with Douglas-fir seedlings after slash was burned. The shelterwood method was used because of the difficulty of obtaining satisfactory tree regeneration on south-facing slopes. Approximately 44 m^2/ha or 60 % of the total basal area was removed from the shelterwood watershed using tractor and high-lead techniques. Harvesting significantly increased annual water yields for both treatments (Harr et al. 1982). Average increases were 380 mm (30 %) for the first 4 years after clearcutting and 200 mm (22 %) for the shelterwood. Water yields were declining by the 5th year.

The annual runoff results for clearcutting on this set of watersheds and those harvested earlier (Rothacher 1970) were similar. The results from the shelterwood and earlier patch cutting also were similar. Logging resulted in fewer low-flow days and greater summer volumes on the treated watersheds relative to the control. An analysis of peak flows and peak flow timing did not indicate changes related to logging. Streamflow increases from the second-growth watersheds also were attributed to reduced ET of the residual vegetation following harvesting (Harr et al. 1982).

Current work on H. J. Andrews has moved away from a focus on commercially logged watersheds toward an interdisciplinary program of ecosystem science (USDA Forest Service 2009), reflecting the general direction of forest research and management in recent years. Researchers on the forest have conducted research on dead wood in old-growth forest streams, probing the role of wood jams in providing calm pools where fish can rest, gravel bars for spawning, and cover from predators. Their work has led to changes in stream management practices on forestlands. The ecological value of dead wood on land has also been examined, yielding valuable information on the role of dead wood in wildlife habitat, carbon dynamics, and nutrient cycling (Geier 2007; Luoma 2006). Geier (2007) describes the forest as becoming a natural and human environment that links people, place, and community with an emerging vision of ecosystem management. More information about H.J. Andrews and a bibliography can be found at http://andrewsforest.oregonstate.edu/.

14.2.8 Watershed Research in the West: A Summary

Research studies conducted at the Sierra Ancha Experimental Forest, Beaver Creek Watersheds, the Fraser Experimental Forest, and the H.J. Andrews Experimental Forest were initially designed to evaluate treatments to achieve a compromise between water yield augmentation and sound silvicultural practices to sustain timber production. The first treatments determined the maximum amounts of water available after clearcutting. Subsequent treatments evaluated silvicultural options to enhance and sustain both water and timber resources. While neither timber nor water is the prime resource in many areas of the West today, this situation is changing. The demands for water will surely increase as the West's population increases and climate change-related droughts expand. Research at the experimental forests and at other locations will alert managers about the potentials and limitations of managing forestlands for water production. There is renewed interest in silvicultural practices as overly dense stands are viewed as potential sources for dangerous and damaging wildfires especially in the wildland–urbaninterface. The experimental forests provide important information for land management and its impact on wildlife and recreation. Determining and quantifying the role of forests as carbon sinks is an important new area of research on many experimental forests. These sites continue to provide sources of long-term forest monitoring that are of local, national, and international importance to scientists and land managers studying forest influences over a wide range of forest environments (i.e., arid, high elevation, high precipitation areas).

14.3 Experimental Forests of the East

The hydrologic role of forests in watershed management has received considerable research attention east of the Rocky Mountains in the last century. Experimental forests and watersheds across this vast region have focused attention on how forest management and land-use changes affect the water resource. Examples of experimental forests and watersheds in the Southeast, Northeast, and Upper Midwest are presented to illustrate the contributions of their research programs to each respective region. With the exception of the Wagon Wheel Gap study in Colorado (Bates and Henry 1928), much of the early research concerning forest influences on water flow began in the Southeast at the Coweeta Hydrologic Laboratory (Jackson et al. 2004).

14.3.1 Coweeta Hydrologic Laboratory

Questions about forest influences on streamflow and flooding in the southeast USA led to the establishment of the Coweeta Hydrologic Laboratory in 1934 (Hornbeck and Kochenderfer 2004; Jackson et al. 2004; Swank and Crossley 1988). The Coweeta Hydrologic Laboratory is located in western North Carolina in the Nantahala Mountain Range of the Blue Ridge Physiographic Province. Coweeta occupies 2,185 ha and is composed of two east-facing watersheds (Coweeta Creek and Dryman Fork) that range in elevation from 670 to 1,580 m. Multiple sub-catchments (Fig. 14.4) have been used for manipulative studies in the main treatment watershed (Coweeta Creek). Coweeta is one of the longest continuous watershed and

Fig. 14.4 Streamflow on Coweeta Watershed 17 is monitored by a 90-degree v-notch weir. The mixed mature hardwood forest on this 13.5 ha watershed was cut in 1942 and replaced by planted eastern white pine (*Pinus strobus* L.) to evaluate the impacts of type conversion on water yields (Swank and Miner 1968). Water yields decreased relative to the hardwood forest as the pine crowns closed and evapotranspiration and interception increased. (Photo courtesy of the Coweeta Hydrologic Laboratory.)

ecosystem studies in North America, guided by the philosophy that "…the quantity, timing, and quality of streamflow provide an integrated measure of the success or failure of land management practices" (Jackson et al. 2004).

14.3.1.1 Studies of Water Flows

In the early 1960s, research focused attention on developing a better understanding of how forests influence runoff, streamflow, and flooding in the Southeast. Hewlett (1961), Hewlett and Hibbert (1963), and Betson (1964) discovered that stormflow and floods in southeastern forested catchments are the product of variable source areas. Importantly, they determined that subsurface flow in forested catchments was the major pathway of stormflow to channels, not "Hortonian" overland flow that was widely thought to be the cause of flooding from all landscapes at that time. High infiltration capacities of the deep forest soils explained why subsurface flow was the dominant component of stormflow in stream channels. Hewlett and Hibbert (1967) expanded the Coweeta research, finding that the variable source area concept explained flows during rainstorms and for extended inter-storm periods in 24 southeastern and eastern streams. Hewlett and Troendle (1975) subsequently developed one of the early variable source area models that incorporated flow paths with topography and landscape position. This relationship provided a better understanding of forestland use and water quality responses in numerous long-term, paired watershed studies.

14.3.1.2 Watershed Studies

Jackson et al. (2004) summarized the key findings that reducing forest cover increases water yields and reforestation decreases water yields. The magnitudes of these changes were proportional to the changes in forest density and solar isolation values. The conversion of hardwoods to pine forests reduced water yields by 30–60 %. However, the conversion of forest cover to grass had little effect on water yields when production of grass was high, but as grass production declined, water yields increased by 15 % and baseflows also increased. Stormflow volumes and peak flow rates increased 11 and 7 %, respectively, following the clearcutting of hardwood forests.

The long-term research contributions of the Coweeta Hydrologic Laboratory enhanced the science of forest hydrology and provided information to better manage forested watersheds of the Southeast. Importantly, this research is as relevant today as in the early years when the focus was on timber harvesting and water yield. This solid foundation illuminates the hydrologic role of forests allowing us to discern the impact of forest fragmentation on impaired water quality, and ascertain how climate change affects both our forests and water. Additional information on the Coweeta Hydrologic Laboratory can be found at http://www.srs.fs.usda.gov/coweeta/.

14.3.2 Hubbard Brook Experimental Forest

The 3,138-ha Hubbard Brook Experimental Forest was established by the United States Department of Agriculture (USDA) Forest Service in the White Mountains of New Hampshire in 1955 as a center for forest hydrology research in the Northeast. Through a cooperative agreement, the Hubbard Brook Ecosystem Study was initiated in 1963 and in 1988 the Hubbard Brook Experimental Forest was designated a Long-Term Ecological Research (LTER) site by the National Science Foundation. Today, it represents one of the most comprehensive and longest continuous ecological studies in North America.

14.3.2.1 Watershed Studies

Paired watershed research began in the 1950s with the aim of better understanding the hydrologic cycle of mature forests in the Northeast (Hornbeck and Kochenderfer 2004). Forest effects on flooding were of particular interest initially, given the wet environment and uniform precipitation of the Northeast. Annual precipitation at Hubbard Brooks is 1,400 mm of which nearly one-third is snow (Federer et al. 1990).

In the Northeast, city-owned watersheds are a primary source for municipal water; the relationship of forest management to water quantity and quality has been a primary interest to municipal watershed managers since the mid-1970s (Hornbeck and Federer 1975). Studies of nutrient cycling and biogeochemical processes were emphasized in the 1960s through the 1990s with the development of cooperative projects and the LTER designation (Hornbeck and Kochenderfer 2004).

One of the most well-known paired watershed experiments at Hubbard Brook is a forest-clearing experiment to determine how complete forest removal influences ET and water yield (Hornbeck and Federer 1975; Hornbeck et al. 1970). In 1965, all of the woody vegetation on one watershed was cut and left where it fell. In the following three summers, herbicides were applied to the watershed to prevent regrowth of vegetation (Likens et al. 1970). For each of the first 3 years following the initial clearing, water yield increased by an average of 290 mm/year with the majority of the increased flow occurring in late summer–early fall. Given that the woody vegetation was not removed from the site, some level of interception by the stems and dead biomass occurred, but most of the increased flow was due to the elimination of transpiration.

A stripcutting experiment to promote regeneration of birch (*Betula* spp.), a valuable timber and aesthetic species, was conducted in 1970. In this experiment, one-third of a watershed was harvested in 24.4 m strips every other year until the entire watershed was harvested. Following the first year in which one third of the watershed was stripcut, water yield increased by 33 mm with the majority of the increase occurring in late summer. This increase in water yield following the strip cut was only about 10 % of the increase observed from the cleared watershed, although 33 % of the watershed was harvested. The difference was explained by both rapid regrowth of vegetation within the strips and the high interception and transpiration rates of trees along the border of uncut strips with roots extending into the moist soil in the harvested strips.

14.3.2.2 Relevance of Results

The relevance of the two watershed experiments became apparent to municipal watershed managers in the Northeast. The potential for manipulating forest cover to increase water yield was minimal and could not be sustained when using an accepted silvicultural practice. By clearcutting, annual water yield could be increased by 100–250 mm, but the increases diminish rapidly with forest regrowth (Hornbeck and Kochenderfer 2004). The prolonged water yield increases observed in other regions of the country, such as at Coweeta and Fraser Experimental Forests, could not be duplicated in the Northeast because of the combination of shallow soils and rapid regeneration. The roots of woody and herbaceous regeneration can fully occupy a shallow soil mantel and utilize all the available soil water including any surpluses created by removing the original cover. Analysis of postharvesting response further indicated that increases in water yield were lower during dry years than wet years. Although clearing and using herbicide to eliminate regrowth increased water yield by nearly 300 mm, the combination treatment had serious water quality and nutrient cycling impacts. Nitrate concentrations increased from 2 to 80 ppm following the clearing and herbicide treatment (Hornbeck and Federer 1975; Likens and Bormann 1995). This level of nitrate is far above drinking water standards of 45 ppm.

Increases in water yield following forest removal raised questions about possible increases in stormflow and flooding. However, 13 major rainstorms following forest clearing were found to increase stormflow by an average of 11 mm per storm, with a maximum increase of 30 mm (Hornbeck and Federer 1975). Since rarely would more than 25 % of any watershed be cleared at any point in time, the effects of accepted forest harvesting practices on stormflow and flooding would be even less than what was observed in the paired watershed experiment. Increases in flood-producing snowmelt following clearing was also considered negligible, given the limited areas undergoing clearing at any one time and the natural desynchronization of snowmelt in the mountainous areas of the Northeast (Federer et al. 1972). Again, a small soil moisture reservoir quickly depleted by transpiration from new vegetation negates the impact of forest harvesting on water yield and peak stormflows in comparison to results from other experimental forest sites with deeper soils, long vegetation recovery periods or both. A recent publication has summarized long-term trends developed from ecosystem research at Hubbard Brook (Campbell et al. 2007). Additional information on Hubbard Brook can be found at the following website: http://nrs.fs.fed.us/ef/locations/nh/hubbard-brook/.

14.3.3 Marcell Experimental Forest

The 1,141-ha Marcell Experimental Forest (MEF) was established in 1960 in the Upper Midwest to study the physical, silvicultural, and hydrological aspects of peatlands and how peatlands affect forest productivity, water availability, and water chemistry (Bay 1966, 1962; Boelter and Verry 1977). The MEF was established to fill a geographic and ecological void in the USDA Forest Service Experimental Forest and Range network of sites. Located approximately 42 km north of Grand Rapids, MN, USA, the area was considered to be representative of upland/peatland forests in the Upper Midwest. Bay (1966) emphasized the need for fundamental hydrologic studies, given the prominence of the 6.1 million ha of organic soils in headwater watersheds of the northern Lake States. Research at Marcell was directed by R. Bay and S. Verry, and is currently directed by R. Kolka and S. Sebestyen. The following summary represents 50 years of research conducted at Marcell that is described in a book edited by Kolka et al. (2011).

14.3.3.1 Process Studies

Fundamental studies were initiated in the 1960s to determine the hydrologic characteristics of organic soils and ET from peatlands. The hydrologic characteristics of organic soils in peatlands were studied by Boelter (1966, 1965, 1964) and Nicholes and Boelter (1984); they developed relationships among fiber content, bulk density, ash content, water storage capacity and water retention, hydraulic conductivity, drainable porosity (specific yield), and von Post degree of humification for organic soils at MEF. These studies provided the foundation for understanding and explaining peatland responses to rainfall and snowmelt in subsequent experimental watershed studies (Boelter and Verry 1977; Verry 1997, 1975).

Studies of ET using lysimeters, energy budgets, and water budgets demonstrated the dominance of evaporative processes in peatland systems. Nichols and Brown (1980) conducted growth chamber studies and found that evaporation rates from sphagnum moss ranged from 0.291 mm/h) at 8.9 °C to 0.558 mm/h at 25.3 °C and were from 1.3 to nearly 2 times the evaporation rates of free water surfaces. Subsequent field studies using eddy correlation methods reported ET rates in a sphagnum bog (May to early October) to average 3.6 mm/day, but ranged from 0.9 to 6.0 mm/day (Verma et al. 1993). Water budget studies of two watersheds with forested peatlands and upland aspen forests found that ET from May 1 to November 1 ranged from 87 to 121 % of Thornthwaite potential evapotranspiration (PET; Bay 1967a, b). Verry and Timmons (1982) reported that ET of a black spruce (*Picea mariana*) forested sphagnum bog, determined as the residual of the water balance, equaled the Thornthwaite PET. From these studies, we can conclude that ET in peatlands is at or near the PET rate as long as the water table is within 30 cm of the soil surface. As a result, ET from peatlands in northern Minnesota averages about 500 mm/year with annual average precipitation of 775 mm/year (Verry 1997).

14.3.3.2 Watershed Studies

Studies of silvicultural treatments on upland and peatland forests provided insight into the hydrologic characteristics and water budgets of these ecosystems (Fig. 14.5). Verry (1986) summarized the hydrologic response of forest harvesting in the Northern Lake States, based largely on the research at the MEFs. Among important results from silvicultural treatments was the finding that clearcutting strips of black spruce and complete clearcutting in a peatland did not change annual water yield (Brown 1972). However, harvesting caused water tables and streamflow to rise during the wet spring period, but it resulted in water tables and streamflow falling below predicted values during the summer dry period. The increase in flow during the spring was explained by the reduced interception losses due to removal of the black spruce. The lower flow rates in the summer following forest harvesting were due to the changes in the vegetative conditions at the forest floor. Following harvesting, the grass-sedge cover on the forest floor was exposed to greater solar energy and wind that promoted higher ET. In response to the changed microclimatic

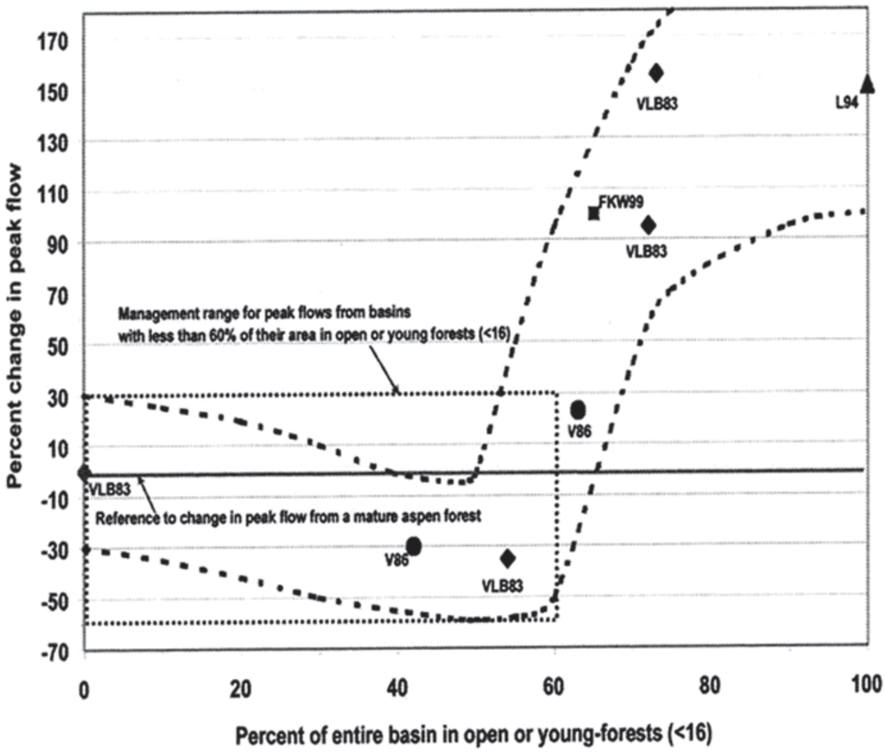

Fig. 14.5 Relationship between peak discharge response to percentage of basin in open land or young forests in the Midwest (Verry et al. 2004). Data points are from individual paired watershed experiments (Verry et al. 1983), double mass curve historical evaluations (Verry 1986), historical geomorphic and modeling analyses (Fitzpatrick et al. 1999), and modeling of upland/peatland watersheds (Lu 1994)

conditions, the grass-sedge biomass in the clearcut strips increased fivefold in the first growing season following tree removal. Furthermore, these species are apparently more physiologically active and have higher transpiration rates in the summer period than did the black spruce.

In contrast to the black spruce watersheds, harvesting of aspen (*Populus* spp.) in the upland portion of a peatland-upland watershed increased annual water yield initially by an average of 90 mm/year (Verry 1972). The increase in water yield was reduced to zero in 12–15 years as a result of aspen regeneration. Snowmelt produced stormflow peaks and stormflow volumes that doubled for 2 years following upland aspen clearcutting. For snow and rain periods, the average annual peak flow (recurrence interval of 2 years) increased 71 % after clearcutting (Verry et al. 1983).

Snowmelt peak response to forest harvesting varied according to the percentage of the watershed that was clearcut (Verry et al. 1983). Clearcutting an entire watershed will double snowmelt peaks, whereas clearcutting 30–50 % of the watershed will reduce snowmelt peaks by as much as 30 % compared to a watershed with a mature mixed aspen forest. Partial cutting desynchronizes snowmelt, and, thus, snowmelt runoff at the watershed outlet. This finding was particularly useful for land-use planners; by tracking the percentage of any watershed that is non-forested through development or timber harvesting, the goal of maintaining at least 50 % forest cover will not increase snowmelt peaks. Computer modeling of streamflow response to timber harvesting, using the paired watershed data at Marcell and long-term precipitation records in the region, showed that clearcutting has a minimal effect on large floods with recurrence intervals in excess of 20–25 years (Lu 1994; Verry 2000). Additional information about the MEF can be found on the website: http://nrs.fs.fed.us/ef/marcell/.

14.3.4 Watershed Research in the East: A Summary

Watershed research in the eastern and midwestern USA also has focused on how forest management and land-use changes have affected water yields and water quality. These issues are important particularly because of the population growth in these regions. Many urban areas depend on their forested watersheds for high quality water that does not require intensive purification. The research in the East has been a combination of basic hydrologic process studies and traditional paired watershed experiments. Research results, such as the relationship between forest treatments and water yield impacts over time, support the general conclusions from research in the West. Pioneering work at Coweeta showed how common land-use practices affected water resources. Subsequent research explained how water moves through the watershed's soil and geological mantle and that all areas are not equally productive sources for water. The importance of transpiration by postharvest replacement vegetation, especially where soils are shallow, was demonstrated at Hubbard Brook. Research at Marcell developed a basic understanding of the hydrology of peatlands and the impacts of land management options. Information from the experiments is the basis for the development of computer models used to explain and predict the impacts of present or future management on water resources.

14.4 Conclusions

A controversy in the early twentieth century concerned the relationship between forests and streamflow. Many foresters maintained that forests reduce surface runoff and help to regulate streamflow. Others believed that only precipitation was important. The evidence in favor of the importance of forests resulted in the Weeks Act of 1911 that allowed for the purchase of forested lands to protect navigable streams and rivers (Dana 1956). Experimental forests were established to answer many questions about forestry and forest resource management. Common key questions concerned the natural role of forests and how various common silvicultural prescriptions and land-use options affect streamflow quantities, peak flows, and timing. In the West, a goal was to clarify the interconnection between forests and snowpacks and how management impacts these resources. Concerns about soil erosion and general site deterioration were also important in the West and Southeast.

Land managers and the public raised questions usually driven by local or regional interests. Maintenance and enhancement of adequate water supplies were, and still are, important concerns throughout the USA. One objective of research on experimental areas surrounding Fort Valley and at Hubbard Brook was to improve water yields and to clarify the forest role in providing water for downstream users. A common question is: "Will harvesting during a drought increase water yields?" Adequate water supplies are also an issue in the humid Northeast where periodic droughts have caused some water restrictions in downstream metropolitan areas such as New York City. Snowpacks are an important source of water throughout the Mountain West, and their management is vital to the City of Denver, Phoenix Metropolitan Area, Salt Lake City, Las Vegas, Los Angeles, Portland, Seattle, and to other western urban centers (Dissmeyer 2000). The impacts of common forestry practices on streamflow quantities and seasonal timing are important issues in the Pacific Northwest with its important fisheries resources, and in the peatlands of the Upper Midwest.

Researchers and staffs assigned to the experimental forests discussed above and to other research locations throughout the USA attempt to provide governmental and private land managers and the general public with information for planning forest treatments and interpreting the impacts on water. Climate goes through cycles and water is a critical resource when there is too much or too little. People look to the forests with hope when there is a drought and when there are floods. Scientists working in the field of watershed management attempt to provide answers for feasible and relevant options. While timber production and water yield augmentation are no longer the prime forest resources in many regions, knowledge gained from USDA Forest Service experimental forests has provided information for more holistic management that includes wildlife populations, recreational opportunities, and livestock management. Increasing demands for water in the future could once more increase interests in managing forestlands for water production.

Land and water managers are currently planning for the consequences of climate change on water supply and flood flows. One of the most important aspects of the Experimental Forest System is the availability of long-term hydrologic and meteorological records. It is particularly relevant now as society considers a future of climate change. These records can be used in simulation models to determine how the climate is changing and at what rate. Linking climate data with long-term vegetation trends provides insight to what our future landscape could look like. The 1950s drought in the Southwest caused large-scale changes in the region's forests and woodlands. Such droughts are a current concern in the region. Will these changes be duplicated by the current drought or a generally more arid environment? Changes in climate and vegetation will affect the regional hydrology. Watershed mangers can modify silvicultural treatments to adjust to these changes, depending on the rate of change. One option is to maintain more open stands of healthier trees that could survive without the excessive competition from their neighbors, but markets for intermediate harvests and mature tree harvests need to be redeveloped. Treatments to mitigate the potential for wildfires are being implemented and will become more common. How do they affect water resources from the forests? Experimental forests will become more important as outdoor laboratories providing scientific answers to questions about climate change treatment options, especially in view of wildfire concerns, landscape dynamics and management, carbon sequestration, and hydrology.

References

Alexander RR (1969) Seedfall and establishment of Engelmann spruce in clearcut openings: a case study. Research Paper RM-53, USDA Forest Service

Alexander RR (1971) Initial partial cutting of old-growth spruce-fire. Research Paper RM-76, USDA Forest Service

Alexander RR (1973) Partial cutting in old-growth spruce-fir. Research Paper RM-110, USDA Forest Service

Alexander RR, Edminster CB (1980) Management of spruce-fir in even-aged stands in the Central Rocky Mountains. Research Paper RM-217, USDA Forest Service

Alexander RR, Edminster CB (1981) Management of lodgepole pine in even-aged stands in the Central Rocky Mountains. Research Paper RM-229, USDA Forest Service

Alexander RR, Watkins RK (1977) The Fraser Experimental Forest, Colorado. General Technical Report RM-40, USDA Forest Service

Baker MB Jr (Comp) (1999) History of watershed research in the Central Arizona Highlands. General Technical Report RMRS-GTR-29, USDA Forest Service

Baker MB Jr, Ffolliott PF (1998) Multiple resource evaluations on the Beaver Creek watersheds: an annotated bibliography (1956–1996). General Technical Report RMRS-GTR-13, USDA Forest Service

Baker MB Jr, Ffolliott PF (1999) Interdisciplinary land use along the Mogollon Rim. In: Baker MB Jr (comp) History of watershed research in the Central Arizona Highlands. General Technical Report RMRS-GTR-29, USDA Forest Service, pp 27–34

Bates CG, Henry AJ (1928) Forest and streamflow experiment at Wagon Wheel Gap, Colorado. U.S. Weather Bureau monthly weather review, Suppl 30

Bay RR (1962) Establishment report, Marcell Experimental Forest. USDA Forest Service, (Chippewa National forest and adjacent private, Itasca County, and State of Minnesota lands), p 26

Bay RR (1966) Evaluation of an evapotranspirometer for peat bogs. Water Resour Res 2:437–441

Bay RR (1967a) Ground water and vegetation in two peat bogs in northern Minnesota. Ecology 48(2):308–310

Bay RR (1967b) Factors influencing soil-moisture relationships in undrained forested bogs. In: Sopper WE, Lull HW (eds) Forest hydrology. Pergamon Press, New York, pp 335–342

Betson RP (1964) What is watershed runoff? J Geophys Res 69(8):1541–1552

Boelter DH (1964) Water storage characteristics of several peats in situ. Soil Sci Soc Am Proc 33:433–435

Boelter DH (1965) Hydraulic conductivity of peats. Soil Sci 100:227–231

Boelter DH (1966) Hydrologic characteristics of organic soils in Lakes States watersheds. J Soil Water Conserv 21(2):50–53

Boelter DH, Verry ES (1977) Peatland and water in the northern Lake States. General Technical Report NC–31, USDA Forest Service

Brown JM (1972) Effect of clearcutting a black spruce bog on net radiation. For Sci 18:273–277
Brown HE, Baker MB Jr, Rogers JJ, Clary WP, Kovner JL, Larson FR, Avery CC, Campbell RE (1974) Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. Research Paper RM–129, USDA Forest Service
Buttle JM, Creed IF, Moore RD (2005) Advances in Canadian forest hydrology, 1999–2003. Hydrol Process 19:169–200
Campbell JL, Driscoll CT, Eager C, Likens GE, Siccama TG, Johnson CE, Fahey TJ, Hamburg SP, Holmes RT, Bailey AS, Buso DC (2007) Long-term trends from ecosystem research at the Hubbard Brook Experimental Forest. General Technical Report NRS–17, U.S. Forest Service, Northern Research Station
Dana ST (1956) Forest and range policy its development in the United States. McGraw-Hill, New York
DeBano LF, Neary DG, Ffolliott PF (1998) Fire's effects on ecosystems. Wiley, New York, 333 p
DeBano LF, Baker MB Jr, Gottfried GJ (1999) Providing water and forage in the Salt-Verde River Basin. In: Baker MB Jr (comp) History of watershed research in the Central Arizona Highlands. U.S. Forest Service General Technical Report RMRS-GTR-29, pp 13–18
Dieterich JH (1983) Fire history of southwestern mixed conifer: a case history. For Ecol Manage 6:13–31
Dissmeyer GE (2000) Drinking water from forest and grasslands: a synthesis of the scientific literature. General Technical Report SRS-39, U.S. Department of Agriculture, Forest Service, Southern Research Station, Ashville, NC, 246 p
Elder K, Porth L, Troendle C (2006) The effect of timber harvest on the Fool Creek watershed after five decades. Abstract B21F-01, American Geophysical Union
Federer CA, Pierce RS, Hornbeck JW (1972) Snow management seems unlikely in the Northeast. In: American Water Resources Association national symposium on watersheds in transition, Urbana, Illinois, pp 212–219
Federer CA, Flynn LD, Martin CW, Hornbeck JW, Peirce RS (1990) Thirty years of hydrometeorologic data at the Hubbard Brook Experimental Forest, New Hampshire. General Technical Report NE-141, Northeastern Forest Experiment Station, USDA Forest Service, Radnor, PA
Ffolliott PF, Baker MB Jr (2001) Stripcut-thinning of ponderosa pine stands: an Arizona case study. Research Paper RMRS-RP-34, USDA Forest Service
Ffolliott PF, Gottfried GJ (1991) Natural regeneration after clearcutting in Arizona's ponderosa pine forests: two long-term case studies. Research Note RM-507, USDA Forest Service
Ffolliott PF, Baker MB Jr, Gottfried GJ (2000) Heavy thinning of ponderosa pine stands: an Arizona case study. Research Paper RMRS-RP-22, USDA Forest Service
Fitzpatrick FA, Knox JC, Williams HE (1999) Effects of historical land-cover changes on flooding and sedimentation, North Fish Creek, Wisconsin. USGS Water Resource Investigations Report 99-4083
Fletcher HC, Rich LR (1955) Classifying southwestern watersheds on the basis of water yields. J For 53:196–202
Geier M (2007) Necessary work: discovering old forests, new outlooks, and community on the H. J. Andrews Experimental Forest, 1948–2000. General Technical Report PNW-GTR-687, USDA Forest Service Pacific Northwest Research Station, Portland, OR
Gottfried GJ, DeBano LF (1988) Streamflow and water quality responses to preharvest prescribed burning in an undisturbed ponderosa pine watershed. In: Krammes JS (comp) Effects of fire management of southwestern natural resources. General Technical Report RMFRES-GTR-191, USDA Forest Service, pp 222–228
Gottfried GJ, DeBano LF, Baker MB Jr (1999a) Beginning of water studies in the Central Arizona Highlands. In: Baker MB Jr (comp) History of watershed research in the Central Arizona Highlands. General Technical Report RMRS-GTR-29, USDA Forest Service, pp 7–12
Gottfried GJ, DeBano LF, Ffolliott PF (1999b) Creating a basis for watershed management in high elevation forests. In: Baker MB Jr (comp) History of watershed research in the Central Arizona Highlands. General Technical Report RMRS-GTR-29, USDA Forest Service, pp 35–41

Gottfried GJ, Folliott PF, Neary DG (2008) Contributions of silvicultural studies at Fort Valley to watershed management of Arizona's ponderosa pine forests. In: Olberding SD, Moore MM (tech cords) Fort Valley-a century of research 1908–2008. Proceedings RMRS-P-53CD, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp 86–97

Harr RD (1976) Forest practices and stream flow in western Oregon. General Technical Report PNW-49, USDA Forest Service, 18 p

Harr RD, Levno A, Mersereau R (1982) Streamflow changes after logging 130-year-old Douglas fir in two small watersheds. Water Resour Res 18:637–644

Hewlett JD (1961) Soil moisture as a source of baseflow from steep mountain watersheds. Station Paper 132, Southeastern Forest Experiment Station, USDA Forest Service, Asheville, NC

Hewlett JD (1971) Comments on the catchment experiment to determine vegetal effects on water yield. Water Resour Res 7:376–381

Hewlett JD, Hibbert AR (1963) Moisture and energy conditions within a sloping soil mass during drainage. J Geophys Res 68(4):1081–1087

Hewlett JD, Hibbert AR (1967) Factors affecting the response of small watersheds to precipitation in humid areas. In: Sopper WE, Lull HW (eds) Forest hydrology. Pergamon Press, New York, pp 275–290

Hewlett JD, Troendle CA (1975) Non-point and diffused water sources: a variable source area problem. In: Watershed management, American Society of Civil Engineers, Logan, UT, pp 21–45

Hicks BJ, Beschta RL, Harr RD (1991) Long-term changes in streamflow following logging in western Oregon and associated fisheries implications. Water Resour Bull 27:217–226

Hornbeck JW, Federer CA (1975) Effects of management practices on water quality and quantity: Hubbard Brook Experimental Forest, New Hampshire. In: Municipal watershed symposium proceedings, General Technical Report NE-13, USDA Forest Service, pp 58–65

Hornbeck JW, Kochenderfer JN (2004) A century of lessons about water resources in northeastern forests. In: Ice GG, Stednick JD (eds) A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, MD, pp 19–31

Hornbeck JW, Pierce RR, Federer CA (1970) Streamflow changes after forest clearing in New England. Water Resour Res 6:1124–1132

Ice GG, Stednick JD (2004) A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda MD, 287 p.

Jackson CR, Sun G, Amatya D, Swank WT, Riedel M, Patric J, Williams T, Vose JM, Tretin C, Aust WM, Beasley RS, Wilson H, Ice GG (2004) Fifty years of forest hydrology in the Southeast. In: Ice GG, Stednick JD (eds) A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, MD, pp 33–112

Kolka RK, Sebestyen SD, Verry ES, Brooks KN (eds) (2011) Peatland biogeochemistry and watershed hydrology at the Marcell Experimental Forest. CRC Press, Boca Raton, FL

Leaf CF (1975) Watershed management in the Rocky Mountain subalpine zone: the status of our knowledge. Research Paper RM-137, USDA Forest Service

Likens GE, Bormann FH (1995) Biogeochemistry of a forested ecosystem. Springer-Verlag, New York

Likens GE, Bormann FH, Johnson NM, Fisher DW, Pierce RS (1970) Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed ecosystem. Ecol Monogr 40:23–47

Lu S-Y (1994) Forest harvesting effects on streamflow and flood frequency in the northern Lake States. PhD dissertation thesis, University of Minnesota, Saint Paul, MN, 213 p

Luoma J (2006) The hidden forest: biography of an ecosystem. Oregon State University Press, Corvallis

National Research Council (NRC) (2008) Hydrologic effects of a changing forest landscape. Washington, DC, The National Academies Press, 180 p.

Neary DG, Gottfried GJ, Beyers JL, Ffolliott PF (2006) Floods and sediment yields from recent wildfires in Arizona. In: Proceedings of the 8th federal interagency sediment conference Las Vegas, NV, 2006 April 3–6 (CD–ROM)

Nichols DS, Boelter DH (1984) Fiber size distribution, bulk density, and ash content of peats in Minnesota, Wisconsin, and Michigan. Soil Sci Soc Am J 48:1320–1328

Nichols DS, Brown JM (1980) Evaporation from a sphagnum moss surface. J Hydrol 48:289–302

Noble DL, Ronco F Jr (1978) Seedfall and establishment of Engelmann spruce and subalpine fire in clearcut opening in Colorado. Research Paper RM-200, USDA Forest Service

Olberding SD, Moore MM (2008) Fort Valley Experimental Forest-a century of research 1908–2008. Conference proceedings. Proceedings RMRS-P-55, U.S. Forest Service

Rich LR, Gottfried GJ (1976) Water yields resulting from treatments on the Workman Creek Experimental Watersheds in Central Arizona. Water Resour Res 12:1053–1060

Rich LR, Thompson JR (1974) Watershed management in Arizona's mixed conifer forests: the status of our knowledge. General Technical Report RM-130, USDA Forest Service

Rothacher J (1970) Increases in water yields following clearcut logging in the Pacific Northwest. Water Resour Res 6:653–658

Schubert GH (1974) Silviculture of southwestern ponderosa pine: the status of our knowledge. Research Paper RM-123, USDA Forest Service

Smith FW (1987) Silvicultural research in coniferous subalpine forests of the Central Rocky Mountains. In: Troendle CA, Kaufmann MR, Hamre RH, Winokur RP (tech coord) Management of subalpine forests: building on 50 years of research. General Technical Report RM-149, USDA Forest Service, pp 15–20

Stednick JD, Troendle CA (2004) Water yield and timber harvesting practices in the subalpine forests of the Central Rocky Mountains. In: Ice GG, Stednick JD (eds) A century of forest and wildland watershed lessons. Society of American Foresters, Maryland, pp 169–186

Stednick JD, Troendle CA, Ice GG (2004) Lessons for watershed research in the future. In: Ice GG, Stednick JD (eds) A century of forest and wildland watershed lessons. Society of American Foresters, Maryland, pp 277–287

Steen HK (1998) Forest Service research: finding answers to conservation's questions. Forest History Society, Durham, NC, 102 p

Swank WT, Crossley DA Jr (eds) (1988) Forest hydrology and ecology at Coweeta. Springer-Verlag, New York

Swank WT, Miner NH (1968) Conversion of hardwood-covered watersheds to white pine reduced water yield. Water Resour Res 4:947–954

Troendle CA, Kaufmann MR (1987) Influence of forests on the hydrology of the subalpine forest. In: Troendle CA, Kaufmann MR, Hamre RH, Winokur RP (tech coord) Management of subalpine forests: building on 50 years of research. General Technical Report RM-149, USDA Forest Service, pp 68–78

Troendle CA, King RM (1985) The effect of timber harvest on the Fool Creek watershed, 30 years later. Water Resour Bull 21:1915–1922

USDA Forest Service (1972) National forests in a quality environment. USDA Forest Service, Washington, DC

USDA Forest Service (2009) Experimental forests and ranges: 100 years of research success stories. General Technical Report, FPL-GTR-182, Gail Wells Communication, pp 8–9

Verma SB, Ullman FG, Shurpali NJ, Clement RJ, Kim J, Billesbach DP (1993) Micrometeorological measurements of methane and energy fluxes in a Minnesota peatland. Suo 43(4–5):285–288

Verry ES (1972) Effect of an aspen clearcutting on water yield and quality in northern Minnesota. In: Csallany SC, McLaughlin TG, Striffler WD (eds) Proceedings of a symposium on "Watersheds in Transition" held at Fort Collins, Colorado, June 19–22,1972, American Water Resources Association, Urbana, IL, pp 276–284

Verry ES (1975) Streamflow chemistry and nutrient yields from upland-peatland watersheds in Minnesota. Ecology 56:1149–1157

Verry ES (1986) Forest harvesting and water: the Lake States experience. Water Resour Bull 22:1039–1047

Verry ES (1997) Hydrological processes of natural, northern forested wetlands. In: Trettin CC et al (eds) Northern forest wetlands: ecology and management. CRC Lewis Publishers, New York, pp 163–188

Verry ES (2000) Water flow in soils and streams: sustaining hydrologic function. In: Verry ES, Hornbeck JW, Dolloff CA (eds) Riparian management in forests of the continental eastern United States. Lewis Publishers, Boca Raton, FL, pp 99–124

Verry ES, Timmons DR (1982) Waterbourne nutrient flow through an upland-peatland watershed in Minnesota. Ecology 63:1456–1467

Verry ES, Lewis JR, Brooks KN (1983) Aspen clearcutting increases snowmelt and stormflow peaks in north central Minnesota. Water Resour Bull 19:59–67

Verry ES, Dolloff CA, Manning ME (2004) Riparian ecotone: a functional definition and delineation for resource assessment. Water Air Soil Pollut Focus 4:67–94