A CENTURY OF LESSONS ABOUT WATER RESOURCES IN NORTHEASTERN FORESTS

James W. Hornbeck and James N. Kochenderfer

ABSTRACT. Water resources in forests of the northeastern United States have been a contentious issue throughout the 20th century. The Weeks Law of 1911 recognized the needs to protect water yield and quality, and stimulated long-term interest in the relationships between forests and water. Research has provided a clear understanding of the roles of forests in hydrologic and nutrient cycling, water quality, and sedimentation, and how these roles are affected by human and natural disturbances.

KEY WORDS. Forested watersheds, water yield, flood flows, water quality, sediment

---

Forested watersheds of the northeastern United States experienced tumultuous change during the 20th century. A century that began with the continuation of extensive forest clearing, ruthless logging, and associated wildfires ended with nearly three decades of scientifically based silvicultural and best management practices. Overland flow and erosion early in the century gave way to protective forest floors with high infiltration. Warm, muddy streams gradually returned to clear, potable water. What drove these changes and what lessons have been learned during this century-long metamorphosis? We will attempt to answer these questions within the context of a timeline.

1910 TO 1920 – THE LESSONS BEGIN

Forest-streamflow relationships became a valuable tool for those attempting to rectify the heedless exploitation of forests and water at the turn of the century. Despite controversy over the extent to which streamflow is regulated by forests, the Weeks Law enacted in 1911 provided "for the protection of the watersheds of navigable streams." The legislation ultimately justified the purchase of 9.3 million ha of land for national forests in eastern United States. Protection of water resources always has been an integral part of managing these national forests, and, in turn, an important stimulus for research on watershed management.

In 1911 and 1912, the U.S. Geological Survey conducted a study in northern New Hampshire that included measuring streamflow at weirs built on six small streams, and at natural constrictions in the channels on four larger streams. The study concluded that forest cutting and subsequent burning lowered the rate of infiltration into the soil, causing streams to rise rapidly during storms, and reducing sustained baseflows. These findings were used as support for establishment and purchase of the White Mountain National Forest.

During this period Raphael Zon (1912) first published his treatice "Forests and Water in the Light of Scientific Investigation." This paper prevailed for many years as the definitive work on forest-streamflow relationships, recognizing among other things that forests alone can not prevent exceptional floods. Beyond Zon's paper, scientific information on forest-streamflow relationships remained sparse.

1920 TO 1950 – FORESTS AND FLOODS

By 1920, the logging boom was winding down in the Northeast and natural reforestation of harvested forests and some abandoned agricultural land was well along. However, a pressing need was developing to obtain hard facts about forest influences on streamflow, including floods, low flows, water yield, and erosion/sedimentation. This need was fueled by efforts to develop a national plan for American forestry, and by controversy over whether floods could be controlled by land treatment measures, including reforestation, as opposed to engineering structures.

The desire for data led to the establishment of the Coweeta Hydrologic Laboratory in 1934, and passage of the Omnibus Flood Control Act of 1936. Under this Act, the USDA Forest Service was given responsibility for conducting flood-control surveys on forested watersheds to determine measures required for retarding runoff and preventing soil erosion and sedimentation. Research sought to quantify canopy interception and soil infiltration rates and the role of the forest floor, but progress in documenting forest-flood relationships was slow, and the U.S. Department of Agriculture later was authorized to control flooding by a combination of engineering works and land treatment.

This authorization in effect supported Zon's (1912) premise that forests alone cannot control flooding. Hoyt (1942) suggested that total amount of storage for precipitation in forests of the northeast may not exceed 4 to 6 cm. Hoyt's estimate would prove only slightly conservative; a more appropriate maximum is about 5 to 7.5 cm (Hornbeck 1973). It would be several more decades before studies on gauged watersheds would provide the needed data to fully define relationships of forests to floods in the Northeast (Lull and Reinhart 1972).

1950'S TO 1990'S – HYDROLOGIC CYCLE DEFINED WITH GAGED WATERSHEDS

By the 1950's watershed management research was in full swing at the Northeastern Forest Experiment Station, and paired, gaged watershed studies were in progress on the Fernow (West Virginia) and Hubbard Brook (New Hampshire) Experimental Forests and at the Leading Ridge (Pennsylvania) Watershed Research Unit. Long-term data from control watersheds at these sites have defined the hydrologic cycle for mature forests in the northeast. In general, the Northeast is well watered and precipitation is distributed fairly uniformly throughout the year. In northerly and higher locations, up to 1/3 of annual precipitation can occur as snow, and snowpacks can reach depths of 1/3 to 1 m. Streamflow can be highly variable during the year but on average is highest during late winter and early spring and lowest during summer and autumn when evapotranspiration is at a maximum. Annual evapotranspiration as determined by precipitation minus streamflow is fairly constant from year to year; the coefficient of variation is 5 to 10% (versus 20 to 25% for streamflow and 10 to 15% for precipitation). Flood flows, defined as bankfull or greater levels, can occur at any time of the year, but the most significant flood flows result from rain on snow or large frontal systems associated with hurricanes.

After five or more years of calibration, watershed treatments in the form of forest harvests or forest clearing, sometimes entailing the control of regeneration with herbicides, were initiated at each of these sites. Resulting increases in water yield were of special interest and significance during the early and mid-1960's in light of a several-year drought that gripped the Northeast. Hornbeck et al. (1993, 1997) summarized long term results from these studies and drew three generalizations with regard to impacts on annual water yield: (1) initial increases in annual water yield of up to 350 mm occur promptly after forest cutting; the magnitude is roughly proportional to the percentage reduction in basal area (at least 25 to 30% of basal area must be cut to produce a measurable increase); (2) increases can be prolonged indefinitely by controlling natural regrowth; otherwise, they diminish rapidly, usually within 3 to 10 years; (3) small increases or decreases in water yield can persist for at least a decade (and probably much longer) in response to changes in species composition and climate.

Cutting or clearing of forests in the northeast causes only minor changes in the volume of snowmelt runoff, although the timing of both snowmelt and snowmelt runoff can be significantly advanced (Hornbeck et al. 1997). Thus most increases in water yield after treatments result from water made available by reductions in transpiration and canopy interception. These increases occur primarily during the growing season when transpiration is at a maximum, and primarily as augmentation to low flows. In the Northeast, peak flows usually increase after forest cutting though effects generally decrease as the magnitude of storm runoff increases (Hornbeck et al. 1997; Lull and Reinhart 1967). Thus the effects of forest cutting on flood flows (flow levels exceeding bankfull) are relatively small. Soil moisture usually is recharged completely in mid- to late autumn, and transpiration-induced treatment effects seldom extend to the dormant season.

These findings have important implications for managing the 1,000 or more forested, municipal watersheds in the Northeast. Results from the three study sites indicate that various sizes of clearcuts, with no control of regrowth, can provide immediate increases in annual water yield ranging from 100 to 250 mm. However, such increases diminish fairly rapidly, more so in some areas (Hubbard Brook and Leading Ridge) than others (Fernow) (Hornbeck et al. 1993). When cutting forests with the objective of increasing water yields, consideration must be given to the possible impacts of a change in species composition during regrowth. The long-term results from Fernow and Hubbard Brook show that the desired increases in water yield occurring immediately after cutting may be compromised in later years if hardwoods are converted to softwoods, or if there is a major shift in hardwood species (Hornbeck et al. 1993, 1997).

1950'S TO 1990'S – EROSION, SEDIMENTATION, AND LOGGING PRACTICES

Protecting watershed and channel conditions by minimizing erosion and sediment from logging operations has been a major objective of watershed studies in the northeast since the early 1950's. Most of these studies have been conducted on the Fernow Experimental Forest and have focused on developing the concept of minimum-standard roads, especially for use on private lands where most forest harvesting in the Northeast takes place. Minimum-standard roads are defined as roads built to the lowest standard that will provide a desirable level of utility and environmental protection at an acceptable cost.

Studies at the Fernow have resulted in guides for all phases of road construction, including planning, layout, construction, care after logging (Kochenderfer et al. [n.d.], Kochenderfer 1970), use of gravel to protect against erosion (Kochenderfer and Helvey 1987), sizing of culverts (Helvey and Kochenderfer 1988), and drainage structures (Kochenderfer 1995).

Studies at the Hubbard Brook Experimental Forest have focused on measuring sediment yields from uncut and cutover watersheds (Martin and Hornbeck 1994). Sediment yields collected over several decades averaged 40 kg/ha/yr, among the lowest values in the nation, but were highly variable from year to year depending on the occurrence of unusually large storm events within a given year. Disturbances from cutting and logging increased sediment yields by 10- to 30-fold in the years immediately after cutting and skidding. However, total sediment yields from harvested watersheds remained relatively small and there was minimal impact on stream turbidity.

Results from erosion and sediment studies in the northeast have been tested extensively and incorporated widely in Best Management Practices (BMPs) throughout the region. A general consensus is that terrestrial and aquatic ecosystems in the Northeast can be protected by following known precautions and guidelines for constructing and maintaining roads and skid trails.

1960'S TO 1990'S – WATERSHED ECOSYSTEM ANALYSIS, NUTRIENT CYCLING

In the 1960s, studies on gauged watersheds were expanded beyond water quality and the hydrologic cycle to include the cycling of nutrients and pollutants. As this approach evolved through the 1970's, it took on the term of watershed ecosystem analysis (Hornbeck and Swank 1992). These studies have documented processes, pools, and fluxes for forest nutrient cycles, compiled long-term data sets for chemistry of precipitation and streamflow, and provided a general understanding of relationships between nutrient cycling and forest health and productivity.

These baseline data have been used extensively to evaluate the impacts of disturbances, particularly harvesting and atmospheric deposition, on soil water leaching losses and stream chemistry. At most locations in the Northeast, cutting the forest temporarily increases nutrient leaching, resulting in higher streamwater concentrations of nitrogen (as nitrate), hydrogen, and base cations. The magnitude and timing of these increases are related to the intensity of cutting and stem from: (1) reduced uptake; (2) changes in movement of elements into and out of microbial pools; and (3) accelerated nitrification, decomposition of organic matter, and weathering of inorganic matter (Hornbeck et al. 1987).

The importance of changing ion concentrations to the aquatic biota has received only minimal attention. Noel et al. (1986) and Likens et al. (1970) reported increases in stream periphyton and macroinvertebrates after clearcutting in northern hardwoods, but they did not separate effects of stream chemistry from those of light and temperature. Studies at Hubbard Brook indicate that changes in streamwater ions due to harvest can be moderated by leaving a riparian buffer strip or by extending the harvest over several years (Hornbeck et al. 1987).

When translated to nutrient outputs, the increased ion concentrations in streamwater represent small proportions (< 1%) of total site capitals and apparently do not reduce nutrient availability or forest productivity (Hornbeck et al. 1987). Nutrients removed in forest biomass along with leaching losses induced by acidic deposition are much more important with respect to losses from nutrient capitals of forest soils in the Northeast. Federer et al. (1989) pointed out the potential for significant depletion of base cations, especially calcium, from harvesting and acidic deposition. Bailey et al. (1996) used strontium isotopes to show that rates of rock weathering cannot compensate for current rates of calcium depletion in the Northeast, including those watersheds that are not being harvested. The depletion of calcium and the accompanying mobilization of aluminum have been linked to declining tree health in some areas of the Northeast.

Long-term data on precipitation and streamflow chemistry collected as part of watershed studies have been useful in studying trends and watershed responses. Driscoll et al. (1989) used Hubbard Brook data to show that regional controls of sulfur emissions have reduced concentrations of sulfate in precipitation and streamwater. Edwards and Helvey (1991) reported that since 1971, nitrate and calcium in streams at the Fernow have been increasing gradually, possibly due to nitrogen saturation from high anthropogenic inputs of nitrogen (Aber et al. 1998). This is the only reported incidence in the Northeast of increasing nitrate in streams draining forests free of recent disturbance. Paired watershed studies are in progress at the Fernow Experimental Forest and at Bear Brook Watershed in Maine to determine effects and recovery from artificial acidification, and a Hubbard Brook watershed has received an application of calcium in the form of the mineral wollastonite as part of an effort to better understand processes by which calcium depletion is mitigated.

LITERATURE CITED

ABER, J., AND 9 OTHERS. 1998. Nitrogen saturation in temperate forest ecosystems: hypotheses revisited. *BioScience* 48:921-934.

BAILEY, S.W., J.W. HORNBECK, C.T. DRISCOLL, AND H.E. GAUDETTE. 1996. Calcium inputs and transport in a base-poor forest ecosystem as interpreted by Sr isotopes. *Water Resources Research* 32:707-719.

Driscoll, C.T., G.E. Likens, L.O. Hedin, J.S. Eaton, and F.H. Bormann. 1989. Changes in the chemistry of surface waters. *Environmental Science and Technology* 23:137-143.

Edwards, P.E., and J.D. Helvey. 1991. Long-term ionic increases from a central Appalachian forested watershed. *Journal of Environmental Quality* 20:250-255.

Federer, C.A., J.W. Hornbeck, L.M. Tritton, J.W. Hornbeck, and R.S. Pierce. 1989. Long-term depletion of calcium and other nutrients in eastern US forests. *Environmental Management* 13:593-601.

Helvey, J.D., and J.N. Kochenderfer. 1988. Culvert sizes needed for small drainage areas in central Appalachians. *Northern Journal of Applied Forestry* 5:123-127.

Hornbeck, J.W. 1973. Storm flow from hardwood-forested and cleared watersheds in New Hampshire. *Water Resources Research* 9:346-354.

Hornbeck, J.W., C.W. Martin, and C. Eagar. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. *Canadian Journal of Forest Research* 27:2043-2052.

Hornbeck, J.W., C.W. Martin, R.S. Pierce, F.H. Bormann, G.E. Likens, and J.S. Eaton. 1987. *The northern hardwood forest ecosystem: ten years of recovery from clearcutting.* Research Paper NE-596. Broomall, PA: USDA Forest Service, Northeastern Forest Experiment Station.

Hornbeck, J.W., and W.T. Swank. 1992. Watershed ecosystem analysis as a basis for multiple-use management of eastern forests. *Ecological Applications* 2:238-247.

Hornbeck, J.W., M.B. Adams, E.S. Corbett, E.S. Verry, and J.A. Lynch. 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. *Journal of Hydrology* 150:323-344.

Hoyt, W.G. 1942. Division of BSCE flood committee report. *Journal of Boston Society of Civil Engineering* 29:82-97.

Kochenderfer, J.N. 1995. *Using open-top pipe culverts to control surface water on steep road grades.* General Technical Report NE-194. Radnor, PA: USDA Forest Service, Northeastern Forest Experiment Station.

Kochenderfer, J.N., and J.D. Helvey. 1987. Using gravel to reduce soil losses from minimum-standard forest roads. *Journal of Soil and Water Conservation* 42:46-50.

Kochenderfer, J.N., G.W. Wendel, and W.E. Kidd, Jr. [n.d.]. *Managing your woodlot using minimum standard roads.* Morgantown, WV: West Virginia University Cooperative Extention Service.

Kochenderfer, J.N. 1970. *Erosion control on logging roads in the Appalachians.* Research Paper NE-158. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experimant Station.

Likens, G.E., F.H. Bormann, N.M. Johnson, D.W. Fisher, and R.S. Pierce. 1970. Effects of forest cutting and herbicidal treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. *Ecological Monographs* 40:23-47.

Lull, H.W., and K.G. Reinhart. 1967. Increasing water yield in the Northeast by management of forested watersheds. Research Paper NE-66. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station.

Lull, H.W., and K.G. Reinhart. 1972. Forests and floods in the Eastern United States. Research Paper NE-226. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station.

Martin, C.W., and J.W. Hornbeck. 1994. Logging in New England need not cause sedimentation of streams. *Northern Journal of Applied Forestry* 11:17-23.

Noel, D.S., C.W. Martin, and C.A. Federer. 1986. Effects of forest clearcutting in New England on stream macroinvertebrates and periphyton. *Environmental Management* 10:661-670.

Zon, R. 1912. Forests and water in the light of scientific investigation. In: *U.S. National Waterways Commission, Final Report*, Appendix V, 203-302. Washington, DC: U.S. Government Printing Office.

ABOUT THE AUTHORS

James W. Hornbeck and James N. Kochenderfer are Research Foresters, USDA, Forest Service, Northeastern Research Station, Durham, NH and Parsons, WV.

A Monumental Event

PROCEEDINGS

SOCIETY OF AMERICAN FORESTERS 2000 NATIONAL CONVENTION

Washington, DC • November 16–20, 2000