Watershed Research and Management in the Lake States and Northeastern United States

Elton S. Verry[1], James W. Hornbeck[2], and Albert H. Todd[3]

Abstract.—We present a brief synopsis of the beginnings of watershed management research and practice in the Lake States and Northeastern United States, followed by a summary of significant research findings on many aspects of watershed management, and finally, a review of four examples of how watershed management research has been incorporated into national forest management plans, state best management practices, state river basin projects, and the large, multi state Chesapeake Bay Program.

Introduction

George Perkins Marsh was concerned about changes in the land and streams of Massachusetts, New Hampshire and Maine in the 1860s. He was the first to write about land and water conservation in 1864 when he published *Man and Nature.* In 1902, J. T. Rothrock, Pennsylvania's first Director in the Department of Forestry also expressed concern about how land and water interact:

> "In all our alluvial valleys the frequent freshets work greater or less damage to the farm land. In fact, it can hardly be said that the beds of any of our rivers, which flow through wide valleys, are constant. They not only have entirely deserted the ancient water courses, leaving them off as back channels to one side or the other, but they are changing them from year to year before our eyes. . . Whilst it is true that a large quantity of valuable soil is sometimes deposited by these freshets on the surface of the land, it is also equally true that this same soil has come from the margin or river bank of somebody else's holding. (Rothrock 1902)"

[1] *Research Forest Hydrologist, North Central Research Station, U.S. Department of Agriculture, Forest Service, Grand Rapids, MN*

[2] *Research Forest Hydrologist, Northeastern Research Station, U.S. Department of Agriculture, Forest Service, Durham, NH*

[3] *EPA Liason, Northern Area State and Private Forestry, U.S. Department of Agriculture, Forest Service, Chesapeake Bay Program, Annapolis, MD*

The concept that land-use change (or more precisely, how land was managed) could change river flow dynamics and result in erosion of channel banks was readily accepted by Rothrock. Twenty six years later, Raphael Zon, Director of the Lake States Forest Experiment Station, published his treatise: "Forests and Water in the Light of Scientific Investigation" (1927), and set down his conclusions of land and water interactions based primarily on case studies.

In the mid 1950s, watershed research focused on statistically valid, paired-watershed experiments and on replicated plot studies of hydrological processes. Bob Dills at Michigan State University detailed watershed management research needs in the forests of the Lake States in a cooperative agreement with the Lake States Forest Experiment Station in 1956. Sidney Weitzman, Assistant Director at the Experiment Station, had recently moved from West Virginia and new studies on watershed management at the Fernow Experimental Forest. Weitzman and Dills called for research on the impacts of forest management on water resources, and on the science of water. Weitzman and Forest Service colleagues decided to establish a network of experimental watersheds and they were careful to assign Forest Service watershed research stations on the basis of broad geologic regions: the central Appalachians of West Virginia (the Fernow Experimental Forest), the flat lands of New Jersey (Pequannock municipal watersheds), the White Mountains of New Hampshire (the Hubbard Brook Ecosystem Studies), the Driftless Area of SW Wisconsin (the Coulee Experimental Forest), the sandy outwash areas of central Michigan (the Udell Experimental Forest), and the moraine and peatland areas of Minnesota (the Marcell Experimental Forest). Studies on these Forest Service research watersheds, early USGS work in New York by Schneider and Ayer (1961), and university watershed research by Penn State University at the Leading Ridge Experimental Forest formed the nucleus of a mid-century push to bring rigorous evaluation to Rhaphael Zon's treatise. In 1965, Sopper and Lull edited the International Symposium on Forest Hydrology held at Penn State University and summarized much of what was known then about watershed management world-wide.

Much of the Forest Service work was born out of the forest influences work of Zon, Hardy, Kitteridge, and Stoeckler, but their mid-century effort focused new research knowledge on small watersheds. In the 1960s, the

U.S. Army Corps of Engineers approached large river basin management through a series of compendiums on river basin assessments throughout the United States. In agricultural areas, the Soil Conservation Service began the task of using soil conservation measures to manage water on the land and in streams. Carlos Bates' examination of the impact of large scale agricultural development in Wisconsin in the 1950s is an example and, later, both Stanley Trimble (1977, 1982, 1993), and James Knox (1971, 1987, 1989) did evaluations of exceptional extent and detail on agriculture's impact on stream and river geomorphology in southwestern Wisconsin's Driftless Area.

We cannot explore all of the watershed research and watershed management efforts that have occurred in the last half century, but we will summarize some of the knowledge gained from watershed research, and survey examples of how research findings have been incorporated into watershed management approaches. These examples include national forest management plans (the White Mountain National Forest in New Hampshire), incorporation of research into state forestry Best Management Practices (three versions of Minnesota's Department of Natural Resources and other NRCS-led, River Basin Projects), and large area, multi state, and multi agency watershed management plans (the Chesapeake Bay Plan).

Nutrient Cycling and Water Chemistry Research

Studies of forest nutrient cycles have been incorporated with watershed studies in the northeast since the mid 1960s (Hornbeck and Swank 1992). The studies have resulted in documentation of processes, pools, and fluxes in forest nutrient cycles (Likens and Bormann 1995); long-term data sets for chemistry of precipitation and streamflow (Likens et al. 1998, Edwards and Helvey 1991); and a general understanding of relationships between nutrient cycling and forest health and productivity (Bormann and Likens 1979).

These baseline data have been used extensively for evaluating the impacts of disturbances, especially harvesting and atmospheric deposition, on soil water leaching losses and stream chemistry. At most locations in the northeast, cutting the forest will result in increased leaching and thus higher streamwater concentrations of nitrogen (as nitrate), hydrogen, and base cations. This is true in the Sault Ste. Marie, Ontario hardwood area also, but clearcutting does not increase nitrate concentrations in other areas of the Lake States. The magnitude and timing of the increases are related to the intensity of cutting and stem from changes in a number of processes including:

- reduced uptake;
- movement of elements into and out of microbial pools;
- accelerated nitrification;
- accelerated decomposition of organic matter; and
- accelerated weathering of inorganic matter (Hornbeck et al. 1987).

Phosphorous is apparently not affected by these changes in processes and remains tightly bound in forest soils, even after harvests (Wood et al. 1984) and moderate fires, but can be released from severe fires that consume the forest floor above bedrock.

Northern hardwood forests are the most susceptible to increased soil water leaching and increases in streamwater ion concentrations. For example, intensive, even-aged harvests in New England have caused streamwater nitrate to rise from <5 mg/L before harvest to 25 mg/L by the second year after harvest, and calcium to rise from 1-2 mg/L before to 4-5 mg/L after (Martin et al. 1984, Hornbeck et al 1987). In comparison, maximum increases in streamwater nitrate after intensive harvests in other forest types have been 4 mg/L in spruce-fir (Hornbeck et al. 1986), 6 mg/L in central hardwoods of Connecticut, (Hornbeck et al. 1986), and <1 mg/L for central hardwoods in Pennsylvania (Lynch and Corbett 1990) and West Virginia (Patric 1980), and aspen in Minnesota (Verry 1972). The increases in nitrate and base cation concentrations are short lived, returning to pre harvest levels in 3-4 years.

The importance of changing ion concentrations to the aquatic biota has had only minimal study. Noel et al. (1986) and Likens et al. (1970) reported increases in stream periphyton and macroinvertebrates after clearcutting 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). None of the experiments involving commercial harvests resulted in nutrient ion increases that exceeded drinking water standards.

When translated to nutrient outputs, the increased ion concentrations in streamwater represent small proportions (<1%) of total site capitals and do not appear to reduce nutrient availability or forest productivity (Hornbeck et al. 1987). Nutrients removed in forest biomass, coupled with leaching losses induced by acidic deposition, are much more important in terms of losses from nutrient capitals of forest soils in the northeast. Federer et al. (1989), Grigal and Bates (1992), and Grigal (in press) reviewed results from several watershed studies in the Lake States and Eastern United States and pointed out the potential for significant depletion of base cations, especially calcium, due to harvesting and acidic deposition. Bailey et al. (1996) used strontium isotopes to show that rock weathering rates can not compensate for current rates of calcium depletion occurring in the northeast, even from 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 (Shortle and Smith 1988, Lawrence and Huntington 1999).

The long term data on precipitation and streamflow chemistry collected as part of watershed studies are proving useful in studying trends and watershed responses. Driscoll et al. (1989) used the Hubbard Brook data to show that regional controls of sulfur emissions have resulted in decreasing 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 gradually increasing, 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 in West VA and at Bear Brook in ME to determine effects and recovery from artificial acidification (Adams et al. 1993, Rustad et al. 1996), and a Hubbard Brook watershed will soon receive applications of calcium as part of an effort to learn more about calcium depletion.

Precipitation chemistry studies at the Marcell Experimental Forest in Minnesota first highlighted the interaction of upland and wetland nutrient cycling (Verry and Timmons 1975). Acid rain concerns in Europe and Canada soon brought the recognition that the chemistry of the atmosphere played a significant role in watershed response measured in stream and lake chemistry and their biota. The first operating station for the National Atmospheric Deposition Program (NADP) starting July 3, 1978, was located at the Marcell Experimental Forest. It was quickly followed by stations at the Fernow Experimental Forest in West Virginia and the Leading Ridge Experimental Forest in Pennsylvania. Today, more than 200 sites nationwide provide this necessary watershed input data for acidification, nutrient cycling, eutrophication, mercury, and, on occasion, pesticides and radio isotopes.

Realization that precipitation acidity had increased over much of the Northeastern United States spawned hundreds of studies that viewed watersheds as the important integrating unit to evaluate impacts to streams and lakes (Charles 1991). Of primary concern was the reaction of acidic inputs (sulfuric and nitric acid) with base cations (primarily calcium, magnesium) in the watershed soils. Three models of watershed chemistry ILWAS (itegraed lake watershed acidification study), MAGIC (model of acidification of groundwater in catchments), and ETD (enhanced trickle down) were developed at USGS, National Park Service, TVA, and U. S. Forest Service watersheds in the East (Munson and Gherini 1991). Assessments of lake and stream chemistry revealed that 14% of the lakes in the Adirondacks, 16% of the streams in the Catskills, 10% of the streams in West Virginia, and 14,000 lakes in Southeastern Canada were acidic (Charles 1991). The acidic condition of most of these lakes and streams was caused by acidic precipitation, but acid mine drainage, and high concentrations of organic acids also caused water acidification.

Effects of Forest Disturbance on Water Yield

Paired watersheds have been used to study the hydrologic cycle of forests in northeastern United States since the early 1950s. These studies have provided a good understanding of how both abrupt and gradual changes in forest cover affect water yield over time periods on the order of decades. Hornbeck et al (1993) summarized results from 11 separate, treated watersheds at 4 locations in the northeast, including the Marcell, Fernow, and Hubbard Brook Experimental Forests and the Leading Ridge Watershed Research Unit. He determined 3 generalizations regarding changes in water yield:

1. Initial increases in water yield occur promptly after forest cutting, with the magnitude being roughly proportional to percentage reduction in basal area.
2. The increases can be prolonged for an undetermined length of time by controlling natural regrowth; otherwise they diminish rapidly, nearly disappearing within 3-10 years.
3. Small increases or decreases in water yield may persist for at least a decade, and probably much longer, in response to changes in species composition.

Increases in annual water yield for the first year after each of the 11 watershed treatments ranged from <10 to 347 mm. As found in previous summaries (Douglass and Swank 1972, Bosch and Hewlett 1982), the increases were related to reductions in stand basal area. A comparison for all 11 watersheds suggests that reductions in basal area must approach 25% to obtain measurable responses in annual, water-yield. Above this threshold there is some variability in first-year responses among watersheds with similar basal areas cut, but the differences usually can be explained by factors such as configuration and timing of cutting, location of cutting in relation to the stream channel or source area, and whether regrowth was controlled with herbicides.

Flow-duration curves for post-treatment periods at each of the 4 locations show that nearly all changes in water yield result from increases at low flow levels (Hornbeck et al. 1997, Patric and Reinhart 1971, Verry 1972, Lynch et al. 1980). Further, the increases occur primarily in the growing season. Only Hubbard Brook and Marcell Experimental Forests normally have continuous winter snow packs. The timing of snowmelt runoff was advanced by forest treatments at both sites, but total volume of snowmelt runoff was not changed (Hornbeck et al. 1997, Verry et al. 1983).

Some watershed treatments at the Fernow and Hubbard Brook Experimental Forests eventually resulted in decreases in water yield. The decreases at the Fernow resulted from converting hardwoods to conifers, and were not unexpected based on studies showing that evapotranspiration is greater for conifers than hardwoods (Swank et al. 1988). Persistent decreases in water yield starting around the tenth year of natural revegetation on cleared watersheds at Hubbard Brook were unexpected. The decreases are due to pioneer and early successional species that dominate the regeneration during years 10 to 30 and beyond having significantly lower leaf resistances and thus greater transpiration than the trees comprising the mature forest (Hornbeck et al. 1997).

Implications for Municipal Water Supplies

Results from the 4 study sites indicate that various sizes of clearcuts, without 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 and Marcell) (Hornbeck et al. 1993). When cutting forests with an 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 water yield may be compensated in later years if hardwoods are converted to softwoods, or if there is a major shift in composition of hardwood species.

The prolonged increases in water yield that occur after cutting in other regions of the USA, such as from deeper soils of the southeast (Swank et al. 1988) or from slowly regenerating forests of the west (Troendle and King 1985), cannot be expected in the northeast. Shallow soils and rooting depths, shorter growing seasons, lower evapotranspiration, rapid root occupancy and leaf area development by natural regeneration, and complete recharge of soil moisture during every dormant season all act to limit the magnitude and duration of increases in water yield in the northeast.

Bankfull and Flood Peak Flows

Bankfull discharge is considered the channel-forming discharge (Leopold 1994), thus, changes in this discharge (about the 1.5 year recurrence interval discharge) are necessarily accompanied by a change in channel cross section area, channel form, sinuosity, or roughness. Dramatic and stark examples of this have been documented by the SCS in Wisconsin and Minnesota's Driftless Area and by Trimble and Lund (1984) for Wisconsin's Coon Creek Watershed. Evaluation of land use changes from forest to agriculture in northern Wisconsin and Minnesota indicates that bankfull flows double when agriculture land use makes up more than half the basin (Verry 1999). Drainage of wetland and conversion to crops in the Minnesota River Basin more than doubles the average annual peak flow (Prof. K. N. Brooks, personal communication). In 1961, Schneider and Ayer showed that reforesting 58% of a cleared basin in New York decreased dormant season peak flows (both snow and rain) by 47%. The combination of a process-based hydrologic model developed at the Marcell Experimental Forest in Minnesota with long-term weather data also shows that clearcutting aspen forests can increase bankfull flows from snowmelt by 150%, with lesser increases for recurrence intervals up to 25 years (Lu 1994). No changes in peak flows were seen for flows with greater than a 25-year recurrence interval.

Watershed Condition

Sediment Control from Roads and Stream Crossings

Protecting watershed and channel conditions by minimizing erosion and sediment from logging roads and skid trails has always been a major objective of watershed studies in the northeast. The bulk of these studies have been conducted on the Fernow Experimental Forest and have focused on constucting and evaluating minimum-standard roads. Such 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. undated, 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 Hubbard Brook have focused on measuring sediment yields from uncut and cut watersheds (Martin and Hornbeck 1994). Sediment yields collected over several decades averaged 40 kg/ha/yr, which is among the lowest values in the nation (Megahan 1972), but were highly variable from year to year, depending largely upon occurrence of unusually large storm events within any given year. Disturbances from cutting and logging increased sediment yields by as much as 10- to 30-fold in the years immediately after cutting and skidding. However, total 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 extensively tested and widely incorporated in best management practices used throughout the region (Eagan et al. 1998, Briggs et al 1998, Lynch and Corbett 1990, Kochenderfer et al. 1997, Kochenderfer and Hornbeck 1999). A general concensus is that terrestrial and aquatic ecosystems in the northeast can be adequately protected by following known precautions and guidelines for constructing and maintaining roads and skidtrails.

Many studies of culvert sizing for streams have previously provided for the passing of a 25 or 50 year event without overtopping of the road and loss of the culvert. Recently Baker and Votapka (1990) have emphasized the inclusion of fish passage criteria along with road integrity criteria for culvert sizing and placement. Round culverts selected with a diameter equal to the bankfull stream width will provide fish passage during bankfull spawning runs by keeping water velocities inside the culvert low enough for fish to pass through in most eastern streams (Verry 1999). Bridges are best able to pass flows without channel impairment. Temporary bridges, and other temporary stream and wetland crossing options can be used effectively to protect stream and wetland sites (Blinn et al. 1998).

Desirable Stream Conditions and Controlling Bankfull Flow Changes

Changes in bankfull, channel-forming, flows cause channels to change their type (Rosgen 1996, Verry 1999). When channels change their Natural Stream Type, they are unstable and unable to carry the water and debris from their watershed without excessive erosion and sedimentation (Rosgen 1996). Channels within plus or minus 30% of their modal values for entrenchement, width/depth ratio, and sinuosity are normal and constitute a desirable stream habitat condition (Verry 1999). Permanent land use changes from forests to agriculture cause channels to change their type; a process that can take from 1 year to 1 century (see the works of Trimble, and Knox for examples).

Even rapid rates of forest clear cutting without conversion to agriculture can change peak flows. The rate of change is dependent on the range of slopes within the watershed, the amount of land cleared over a period of 15 years, and on the size of the watershed evaluated. Bankfull flow rate increases of 100% can occur on flat land watersheds (with slopes generally less than 3%), when 2/3 of their basin is harvested in the span of 15 years on watersheds that are at least 10 square miles in size. Similar increases occur on moraine watersheds (with slopes up to 30%), when 2/3 of their basin is harvested in the span of 15 years on basins that are at least 1 square mile in size (Verry 1999). Mountain watersheds (with slopes up to 60%) can experience bankfull flow changes in basins of at least 3 square miles and with only 1/4 of their basin harvested (or permanently cleared) in the span of 15 years (personal observation (ESV)on the Allegheny National Forest, PA).

Case Studies: Integrating Watershed Research and Watershed Management

White Mountain National Forest

Primary audiences for watershed research in the northeast are managers and consultants working with private, state, and national forests, municipal watersheds, and aquatic resources. National Forests have been especially quick to implement results from watershed research directly onto the landscape and into the planning process. Some examples of implementation on the White Mountain National Forest (WMNF), which spans 750,000 acres in New Hampshire and Maine, are:

Long-term site productivity. National Forests have a responsibility to estimate the effects of their activities, including timber harvest, on long-term site productivity. The Northeastern Research Station and WMNF jointly constructed nutrient depletion tables for base cations, and a variety of forest disturbances, and harvest methods. The tables are used to select silvicultural practices that will provide optimum protection of site nutrient capitals and forest productivity.

Weathering Inputs for Calcium and magnesium. The primary uncertainty in estimating nutrient depletion is the rate at which base cations are supplied to the soil by weathering of minerals. WMNF is the study area for testing a glacial till-nutrient source model that estimates contributions from mineral weathering. The Northeastern Research Station devised the model and is compiling bedrock geology maps to support its use. The project is leading to maps of the WMNF showing weathering rates for calcium and magnesium. These maps are being combined with other factors, such as land use history, to develop standards and guides based on risks for soil nutrient depletion.

Nitrogen cycling and land use history. Nitrogen saturation is a concern because of base cation losses that reduce tree productivity, and elevated, but not dangerous levels of nitrate in streamwater (Aber et al. 1998). Susceptibility to nitrogen saturation is dependent upon past disturbances such as agriculture, forest harvest, and fire. The WMNF is cooperating with the Northeastern Research Station to determine past disturbances, susceptibility to nitrogen saturation, and possible restrictions to harvest and other silvicultural practices that accelerate cation loss.

Hydrology of alpine ski areas. Alpine ski areas existing on WMNF are heavily dependent upon surface waters for making artificial snow. In turn, there is controversy over impacts of extracting water, and again when it melts, on water yield, peak and flood flows, and water quality. Legal challenges regarding these impacts led to a need to better understand the impacts of ski area construction and snowmaking on hydrology, erosion and sedimentation, and water quality. Research on water quality and snow hydrology at the Hubbard Brook Experimental Forest has helped meet this need. Implementation of Hubbard Brook results at several ski areas helped to significantly improve their impacts analysis, and to provide background for the legal challenges regarding environmental impacts.

Best Management Practices and River Basin Projects: Minnesota Experience

Like many states, Minnesota responded to the 1987 Amendments to the Clean Water Act, Section 319 by developing their 1989, Water Quality in Forest Management guide as the "Best Management Practices in Minnesota" (MNDNR 1989). In 1995, the Best Management Practices in Minnesota was expanded and published as Protecting Water Quality and Wetlands in Forest Management (MNDNR 1995). In 1999, a much expanded effort produced Sustaining Minnesota Forest Resources: Voluntary Site-level Forest Management Guidelines (MFRC 1999). This progression of effort attests to the strong leadership at the State Department of Natural Resources to continually review, test, and improve forest management guides. It has witnessed major changes in the social climate, the inclusion of new watershed research, and the continual effort to monitor implementation on the ground.

The initial 1989 guide (104 pages) was produced over two years using a committee of forest managers from county, state, and federal agencies, forest industries, and the University of Minnesota. It was strictly limited to water quality issues and used recommendations for filter strips between roads and streams and for road construction derived from research at the Hubbard Brook Experimental Forests in New Hampshire published three decades earlier. Other recommendations used standard forestry guides for fire, petroleum, and pesticide use. Its implementation set the stage for voluntary guides in Minnesota and for the annual monitoring of their implementation.

The 1995 guide (140 pages) was produced over three years by committee members from the first effort plus members from other federal agencies, loggers, environmental organizations, and fisheries and water divisions of MNDNR. The guide was upgraded with newer road data from the Fernow Experimental Forest in West Virginia and the Coweeta Hydrologic Laboratory in North Carolina, and an extensive section dealing with wetlands relied heavily on research from the Marcell Experimental Forest in Minnesota using the preservation of hydrologic function as a guiding principle.

The 1999 guide (329 pages) was produced with four committees: riparian areas, wildlife habitat, cultural resources, and forest soil productivity. The previous water quality and wetland effort was included as well as a DNR effort on visual quality. This effort was administered by the Department of Natural Resources for the Minnesota Forest Resources Council created by the state Legislature in 1995. Additional organizations represented on the committees included Native Americans, archaeology agencies, other University departments, recreation, landowner, watershed, lake, resort and land management organizations. Unique to this effort was the initiation by the Forest Resource Council of several research projects on watersheds in the state.

Mike Phillips with the Minnesota Department of Natural Resources has shepherded all three of these efforts and is responsible for their monitoring programs. He recently offered this advice: "The involvement of stakeholder groups in the development of BMPs and other forest practice guidelines requires more patience and time. Once agreement is reached, however, implementation will likely be more rapid and effective since there is a greater probability that the interest groups have bought into the product produced. The BMPs or other forest practice guidelines developed by consensus are more likely to reflect a balance of science, practicality, and economics. There is also greater likelihood that trust will develop among the many stakeholders involved in BMP development, which is necessary for successful program implementation (Phillips et al. 1999)."

State BMPs have come a long way and have routinely incorporated watershed research, however, even the last effort in Minnesota was restricted by the Legislature to consider only site-specific guides. A newly constituted Minnesota Forest Resource Council has now begun the task of considering landscape-level guides for forest management. At each step forestry has come closer to incorporating the concepts of watershed management.

Many other units of county, state and federal governments have already addressed watershed-wide management through the establishment of 43 Watershed Districts in Minnesota administered by the state Board of Water and Soil Resources, 75 Clean Water Partnerships, county water management plans, and River Basin projects coordinated by the Natural Resources Conservation Service and the U. S. Forest Service, State and Private Forestry Division. Just one example of the latter is the Nemadji River Basin Project that spans parts of northern Wisconsin and Minnesota, incorporates 12 advisory subcommittees and seeks administrative implementation from local county boards (NRCS 1998). Forest Service and University of Minnesota research has been incorporated into basin-wide, landscape-scale recommendations that address the amount of harvested and cleared agricultural land with sub-basins of the watershed.

Chesapeake Bay Program

The Chesapeake Bay is the nation's largest and, because of its shallowness, the nation's most productive estuary. It is this shallowness that causes its amazing productivity and its sensitivity to what goes on in the watershed. Land use largely determines the quality of the water, the vitality of aquatic habitats, and ultimately, the health and resilience of the Chesapeake Bay itself. The Bay helps define the landscape as well as the culture and economy of the region.

A Bay in Trouble

Since the 1970s, there has been a consensus among scientists, government agencies, and concerned citizens that the Chesapeake Bay was in trouble. Drastic declines in fisheries, shellfish, waterfowl, and bay grasses were the effects of more than two centuries of steady development, loss of forests, increasing pollution and runoff, and accumulation of sediment, nutrients, and industrial wastes. Eutrophication and hypoxia are the primary problems. Runoff carrying sediment, fertilizers, manure, and pesticides from agricultural lands, point sources of municipal treated sewage, increasing runoff from urban areas, and atmospheric deposition all contribute to the problem. To restore the Bay, all of these nutrient sources were addressed when the Environmental Protection Agency (EPA) published a major study of the Bay in 1983.

Coordination at the Watershed Scale

The 1983 study brought the states of Pennsylvania, Maryland, Virginia, and the District of Columbia together with the Chesapeake Bay Commission (and federal agencies) in a partnership. Each agreed to work together to develop and implement a coordinated effort to improve and protect water quality and the living resources of the Chesapeake Bay. This action marked a turning point in watershed restoration because it sought to manage the Bay ecosystem as a whole. Subsequent agreements in 1987 and 1992, added a strategy to target efforts in each of the major tributaries basins. Locally-led "tributary strategies", tailored to individual sub-watersheds, built connections between local conditions, issues, and approaches and larger-scale Bay restoration goals for pollution reduction and habitat restoration. The Chesapeake Bay Program has grown into a unique regional institution, guiding and coordinating the Bay-related activities of literally hundreds of federal, state, local and intergovernmental agencies, and working with dozens of private business, civic, and environmental organizations.

Forests and the Bay

In the 1600s, 95% of the watershed was forested. The forests served as a continuous living filter and regulator of the Bay's environment. In the mid 1800s, 50% of the Bay's watershed was converted to farms, pastures, cities, and industry. Reforestation of abandoned agricultural land gradually raised forest land to 60% of the basin; however, for the first time in nearly a century, the percent of forest lands is once again declining. Although some forest land is still cleared for agriculture, as much as 100 acres per day have been converted to urban lands during the last 20 years. It is clear that the long term stewardship of the Chesapeake Bay depends in part on the health and stewardship of forests in the watershed.

The USDA Forest Service, Northeastern Area State and Private Forestry, joined the Bay Program partnership in 1989. Using a foundation of basic watershed management and forest stewardship principles, new technology and research, and the flexibility of cooperative forestry programs, the Forest Service is demonstrating how forests are part of the long-term solution to managing the Bay's watershed. Working across mixed ownerships, a Forestry Work Group serves as a catalyst to bring together federal, state, local and private resources to implement this approach. "Forest solutions" are developed in three areas:

- *Forest Protection* - Our activities demonstrate that forests have high social values for water supply, recreation, preservation of watershed functions. We show they are critical for aquatic and terrestrial habitat health, and that they and are storehouses of future benefits and uses. We seek to help communities assess their watersheds, educate citizens and design strategies to reduce fragmentation and forest loss where forest lands are threatened by conversion to other land uses.
- *Forest Restoration* - Restoring forests on erodible lands, wetlands, and along streams and shorelines, integrating forests into pollution control for farm runoff and storm water management, and promoting community "green infrastructure" projects in urban areas are the focus.
- *Forest Stewardship* - Properly managed forests retain land in a beneficial land use while supporting local economies. Working with partners in the states and through the Forest Stewardship Program, ecological concepts are integrated into forest management on private lands, and loggers and landowners are educated about BMP application and their benefits to the Chesapeake Bay.

This collaborative effort produced a Chesapeake Bay Riparian Forest Buffer Initiative in 1994. Endorsed by the Bay Program's Executive Council, this effort has resulted in a watershed-wide policy of stewardship to protect and restore riparian forests in the watershed. The Chesapeake Bay Partners have made commitments to improve communication and coordination, build new partnerships, provide additional incentives and funding, and develop education programs for citizens, schools, and practitioners. The Riparian Initiative has restored forests along nearly 500 miles of stream channel.

Managing a Watershed: Lessons Learned

What began as a water quality program has now grown to involve integrated management of land, air, water, and living resources. This integration of knowledge and goals into the institutions of daily life is essential for watershed efforts at both small and large-scale. This is true whether related to forest conservation or pollution prevention. The following ten lessons learned from the Chesapeake Bay Program are sound advice for watershed management approaches everywhere.

1. *Begin by establishing a sound scientific foundation*. Sound watershed management must be based on the best available science and basic data on natural resources. Focus on linkages between land, water, living resources, and people. Admittedly, policy decisions will not always be based on science or a complete watershed assessment, but if basic information is made available in an easily-understandable format, the chances are high that it will be integrated into the decision-making process. Facilitating a meaningful exchange of information between academic and government research and the local management community is essential. Assemble the best existing information first and establish ongoing monitoring to measure progress and test models in the future.

2. *Involve the highest and broadest levels of leadership possible.* There is enormous strength in strong leadership. The direct involvement of State Governors and high federal officials in setting goals and sharing in accomplishments is prerequisite. Only high-ranking officials have the authority to endorse and implement policies and provide the resources needed for program implementation. They should be involved in visible ways. However, just as strong government leaders are important, watershed leaders that emerge from the community must also be embraced and empowered. Seeking out and involving leaders in the watershed is a critical factor in making the watershed approach work.

3. *Embrace clear, strong, and measurable goals*. There is great strength in clear goals and accountability. At the Chesapake Bay Program, highly specific goals include: 40% reductions in nitrogen and phosphorus pollution, eliminating fish blockages in major tributaries, and restoration of bay grasses, wetlands and riparian forests. Goals are that are quantifiable make progress measurable and leaders accountable. Citizens should participate in setting and achieving goals that extend beyond the tenure of elected officials or agency managers.

4. *Invite a broad diversity of participants.* Watersheds and their problems and solutions are complex. Likewise, any watershed management framework should involve a diversity of participants. Watershed management should be inclusive and invite a variety of government, non-profit and private players to contribute unique skills, resources and perspectives. Together, a multitude of players also bring greater political leadership and financial support. At the Bay Program, members of government

work side by side with others from industry, local, and public groups, brought together by common issues and a commitment to a common set of resource goals. Although it requires strong communications efforts, this inclusive process has become a signature of the Bay Program.

5. *Establish incentives and methods for continual cooperation*. The principle incentives are money and public pressure. The active financial involvement of the EPA and other agencies has leveraged millions of state and local dollars. Cost share and assistance programs to meet Bay goals have allowed much of the restoration work to remain voluntary. The commitment to succeed voluntarily (rather than with more regulation) is an incentive in itself. Emerging issues or new strategic approaches and goals are brought to the Executive Council, and "Directives" are signed to renew commitments or define new actions. These high level directives take on the weight of an executive order to participating agencies. The Bay Program has also established more than 50 subcommittees and workgroups to ensure that all interests are represented and that there is continual interaction between participants.

6. *Inform and involve the public*. Keeping the citizenry of the Bay watershed informed is a top priority. Use extensive educational and technology transfer efforts. Management of resources in a watershed like the Chesapeake Bay requires complex political decisions. An informed and vocal public has proven to be the Bay's greatest ally. Honesty, even when findings or progress is disheartening, is critical to maintaining trust and stakeholder commitment.

7. *Choose prevention before restoration or mitigation*. Although it is often more politically appealing to fund many restoration projects, a watershed approach must focus first on ensuring that a solid foundation of preventive conservation measures are in place to ensure that restoration progress does not lose ground. A balanced set of management tools should be developed allowing individual jurisdictions to customize or adapt tools for their application.

8. *Test theories and management approaches on a small scale*. Our scientific knowledge and technologies for watershed management and restoration are continually growing. By studying the effectiveness of strategies in small watersheds through demonstration or pilot projects, we can increase success when these concepts are applied more broadly. These demonstration projects help develop public support, attract partnerships and funding, and build the confidence of political leaders to expand their application.

9. *Regularly reassess goals and progress*. The Bay Program is supported by a strong monitoring effort and has a strong commitment to reassess goals, monitor trends, and measure progress. The health and vitality of living resources serve as an important indicator. Keeping the public informed of findings and maintaining flexibility has helped maintain the integrity of the Program.

10. *Demonstrate results.* Progress in watershed restoration is incremental. Celebrating successes along the way is critical to maintaining momentum. Since the Bay Program began in 1983, phosphorus inputs to the Bay have been reduced by over 30%, nitrogen concentrations are down and total loads are not increasing in spite of an increasing population. Practices for pollution prevention from farm runoff and urban stormwater have improved dramatically. The striped bass fishery has recovered, bay grasses are returning in many areas, oysters are making slow progress, 1000s of miles of stream have been opened to migratory fish, and over 10,000 acres of riparian area and wetland have been restored. Local governments are also taking action to protect stream corridors and open space and adopt smart growth policies. Volunteer efforts are expanding and the increased environmental awareness of the citizenry is easy to observe.

Application of watershed management principles, whether at the site or landscape scale, must use competent watershed analysis of conditions on the ground as a base for action. Learn to read the land (Leopold 1949) and read the river (Leopold 1994), and when you do we have no fear of what you will do, indeed we are excited about what you will do for them.. For a detailed examination of management options for riparian areas in the Lake States, and Northeastern United States see Verry, Hornbeck, and Dolloff (1999).

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Literature Cited

Aber, J.; and 9 others. 1998. Nitrogen saturation in temperate forest ecosystems: hypotheses revisited. BioScience 48:921-934.

Adams, M. B.; Edwards, P. J.; Wood, F.; Kochenderfer, J. N. 1993. Artificial watershed acidification on the Fernow Experimental Forest, USA. Journal of Hydrology 150:505-519.

Bailey, S. W.; Hornbeck, J. W.; Driscoll, C. T.; Gaudette, H. E. 1996. Calcium inputs and transport in a base-poor forest ecosystem as interpreted by Sr isotopes. Water Resources Research 32:707-719.

Baker, C. O.; Votapka, F. E. 1990. Fish passage through culverts. Report No. FHWA-FL-90-006. U.S. Department of Transportation, federal Highway Administration. Washington, D.C. 67p.

Blinn, C. R; Dahlman, R.; Hislop,L.;. Thomps M. .A. 1998. Temporary stream and wetland crossing options for forest management. Gen. Tech. Rep. NC-202. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 125 p.

Bormann, F.H.; Likens, G.E. 1979. Pattern and process in a foretsed ecosystem. Springer-Verlag, New York. 253p.

Bosch, J. M.; Hewlett, J. D. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55:3-23.

Briggs, R. D.; Cormier, J.; Kimball, A. 1998. Compliance with forestry best management practices in Maine. Northern Journal of Applied Forestry 15:57-68.

Charles, D. F. 1991. Acidic Deposition and Aquatic Ecosystems: Regional Case Studies. Springer-Verlag. 747 p.

Dils, R. E. 1956. Watershed management research needs in the forests of the Lake States: A Problem Analysis. Carbon copy, Grand Rapids, MN. 33p.

Douglass, J. E.; Swank, W. T. 1972. Streamflow modification through management of eastern forests. Res. Pap. SE-94. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 15p.

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

Eagan, A. F.; Whipkey, R. D.; Rowe, J. P. 1998. Compliance with forestry best management practices in West Virginia. Northern Journal of Applied Forestry 15:211-215.

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

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

Grigal, D. F.; Bates, P. C. 1992. Forest Soils. A technical paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota. Jaakko Pyry Consulting, Inc. Tarrytown, NY. 155p.

Grigal, D. F. (in press). Effects of extensive forest management on soil productivity. Forest Ecology and Management.

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

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

Hornbeck, J. W.; Martin, C. W.; Pierce, R. S.; Bormann, F. H.; Likens, G. E.; Eaton, J. S. 1987. The northern hardwood forest ecosystem: ten years of recovery from clearcutting. Research Paper NE-596. Broomall, PA. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 30p.

Hornbeck, J. W.; Martin, C. W.; Smith, C. T. 1986. Protecting forest streams during whole-tree harvesting. Northern Journal of Applied Forestry 3:97-100.

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

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

Knox, J. C. 1971. Valley alluviation in southwestern Wisconsin. Annals of the Assoc. of American Geographers. 62(3):401-410.

Knox, J. C. 1987. Historical valley floor sedimentation in the Upper Mississippi valley. Annals of the Assoc. of American Geographers. 77(2):224-244.

Knox, J. C. 1989. Long-and short-term episodic storage and removal of sediment in watersheds of southwestern Wisconsin and northwestern Illinois. In: Sediment and the Environment. IASH Publ. 184: 157-164.

Kochenderfer, J. N. 1995. Using open-top pipe culverts to control surface water on steep road grades. General Technical Report NE-194. Radnor, PA. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 7p.

Kochenderfer, J. N.; Edwards, P. E.; Wood, F. 1997. Hydrologic impacts of logging an Appalachian watershed using West Virginia's best management practices. Northern Journal of Applied Forestry 14:207-218.

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

Kochenderfer, J. N.; Hornbeck, J. W. 1999. Contrasting timber harvesting operations illustrate the value of BMPs. In: J. W. Stringer and D. L. Loftis (eds.) Proceedings 12th Central Hardwood Forest Conference; 1999 February 28-March 2; Lexington, KY:128-136.

Kochenderfer, J. N.; Wendel, G. W.; Kidd, Jr., W. E. Undated. Managing your woodlot using minimum standard roads. Morgantown, WV. West Virginia University Cooperative Extention Service. 29p.

Kochenderfer, J. N. 1970. Erosion control on logging roads in the Appalachians. Research Paper NE-158. Upper Darby, PA. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experimant Station. 28p.

Lawrence, G. B.; Huntington, T. G. 1999. Soil-calcium depletion linked to acid rain and forest growth in the eastern United States. Denver, CO. U.S. Department of the Interior, Geological Survey Bulletin WRIR-4267.

Leopold, A. 1949. *A Sand County Almanac.* Oxford University Press.

Leopold, L. B. 1994. A view of the river. Harvard University Press, Cambrdige, MA. 298 p.

Likens, G. E.; 10 others. 1998. The biogeochemistry of calcium at Hubbard Brook. Biogeochemistry 41:89-173.

Likens, G. E.; Bormann, F. H. 1995. Biogeochemistry of a forested ecosystem. Springer-Verlag, New York. 160p.

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

Lu, Shiang-Yue. 1994. Forest harvesting effects on streamflow and flood frequency in the northern Lake States. PhD Thesis. University of Minnesota, St. Paul, MN. 112.

Lynch, J. A.; Corbett, E. S. 1990. Evaluation of best management practices for controlling nonpoint pollution from silvicultural operations. Water resources Bulletin 26:41-52.

Lynch, J. A.; Corbett, E. S.; Sopper, W. E. 1980. Impact of forest cover removal on water quality. Pennsylvania State University Institute for Research on Land and Water Resources. University Park, PA. Research Paper 23-604. 91p.

Marsh, G. P. 1864. *Man and nature or physical geography as modified by human action*, ed. D. Lowenthal. Cambridge, MA: Harvard University Press.

Martin, C. W.; Noel, D. S.; Federer, C. A. 1984. Effects of forest clearcutting in New England on stream chemistry. Journal of Environmental Quality 13:204-210.

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

Megahan, W. F. 1972. Logging, erosion, sedimentation — are they dirty words? Journal of Forestry 70:403-407.

MNDNR (Minnesota Department of Natural Resources). 1989. Water quality in forest management: "Best Management Practices in Minnesota". St. Paul, MN. 104 p.

MNDNR (Minnesota Department of Natural Resources). 1995. Protecting Water Quality and Wetlands in Forest Management: Best Management Practices in Minnesota. St. Paul, MN 140 p.

Minnesota Forest Resource Council. 1999. Sustaining Minnesota Forest Resources: Voluntary Site-Level Forest Management Guidelines for Landowners, Loggers, and Resource Managers. St. Paul, MN. 329 p.

Munson, R. K.; Gherini, S. A. 1991. Processes influencing the acid-base chemistry of surface waters. In: Acidic deposition and Aquatic Ecosystems: Regional Case Studies. Springer-Verlag, New York. 35-64.

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

NRCS. 1998. Erosion and sedimentation in the Nemadji river basin, final report. Natural Resources Conservation Service and U.S. Forest Service. Duluth, MN. 149 p.

Patric, J. H. 1980. Effects of wood products harvest on forest soil and water relations. Journal of Environmental Quality 9:73-80.

Patric, J. H.; Reinhart, K. G. 1971. Hydrologic effects of deforesting two mountain watersheds in West Virginia. Water Resources Research 7:1182-1188.

Phillips, M. J.; Swift, L. W. Jr.; Blinn, C. R. 1999 . Best management practices for riparian areas. In Riparian Management for Forests in the Continental Eastern United States. Verry, E. S.; Hornbeck, J. W.; Dolloff, C. A. (eds.). Lewis Publishers, Boca Raton, FL. 271-284.

Rosgen, D. 1996. Applied River Morphology. Wildland Hydrology. Pagosa Srpings, CO. 376 p.

Rothrock, J. T. 1902. Statement of work done by the Pennsylvania Department of Forestry during 1901 and 1902. Wm. Stanely Ray, State Printer of Pennsylvania. Chapter VIII. *The Black Willow (Salix nigra, Marsh.) As a Protector of River Banks:* 136-137.

Rustad, L. E.; Fernandez, I. J.; David, M. B.; Mitchell, M. J.; Nadelhoffer, K. J.; Fuller, R. B. 1996. Experimental soil acidification and recovery at the Bear Brook watershed in Maine. Soil Science Society of America Journal 60:1933-1943.

Schneider, W. J.; Ayer, G. R. 1961. Effect of reforestation on streamflow in central New York. Water Supply Paper 1602. United States Geological Survey, Washington D.C. 61 p.

Shortle, W.C.; Smith, K.T. 1988. Aluminum-induced calcium deficiency syndrome in declining red spruce. Science 240:1017-1018.

Sopper, W. E.; Lull, H. W. 1965. International Symposium on Forest Hydrology. Pergamon Press, New York. 813 p.

Swank, W. T.; Swift, Jr., L. W.; Douglass, J .E. 1988. Streamflow changes associated with forest cutting, species conversions, and natural disturbances. In: W.T. Swank and D.A. Crossley (Editors), Forest Hydrology and Ecology at Coweeta. Springer-Verlag, New York, pp. 297-312.

Trimble, S. W. 1977. The fallacy of stream equilibrium in contemporary denudation studies. American Journal of Science. 277:876-887.

Trimble, S. W. 1993. The distributed sediment budget model and watershed management in the Paleozoic plateau of the upper Midwestern United States. Physical Geography 14(3):285-303.

Trimble, S. W.; Lund, S. W. 1982. Soil conservation and the reduction of erosion and sedimentation in the Coon Creek basin, Wisconsin: A study of changes in erosion and sedimentation after the introduction of soil-conservation measures. Geological Survey Professional Paper 1234. United States Gov. Printing Office. Washington, D.C. 35p.

Trimble, S. W. 1983. A sediment budget for Coon Creek basin in the driftless area, Wisconsin, 1853-1977. American Journal of Science 283:454-474.

Troendle, C. A.; King, R. M. 1985. The effect of timber harvest on the Fool Creek Watershed, 30 years later. Water Resources Research 21:1915-1922.

Verry, E. S.; Timmons, D. R. 1982. Waterborne nutrient flow through and upland-peatland watershed in Minnesota. Ecology 63(5):11456-1467.

Verry, E. S.; Lewis, J. R.; Brooks, K.N. 1983. Aspen clearcutting increases snowmelt and storm flow peaks in north central Minnesota. Water Resour. Bull. 19(1):59-67.

Verry E. S.; Hornbeck, J. W.; Dolloff, A. C. 1999. Riparian Management in Forests of the Continental Eastern United States. Lewis Publishers, Boca Raton, FL. 420p.

Verry, Elon S. 1999. Water flow in soils and streams: sustaining hydrologic function. In: E. S. Verry, J. W. Hornbeck, and C. A. Dolloff (eds.). *Riparian Management in Forests of the Continental Eastern United States*. Lewis Publishers, Boca Raton, FL. 67-99.

Verry, E.S. 1987. The effect of aspen harvest and growth on water yield in Minnesota. In: Forest Hydrology and Watershed Management. International Association of Hydrological Sciences publication 167:553-562.

Verry, E. S. 1986. Forest harvesting and water: the Lake States experience. Water Res. Bull. 22(6):1039-1047.

Verry, E. S. 1972. Effect of an aspen clearcutting on water yield and quality in morthern Minnesota. In: American Water Resources Association *National Symposium on Watersheds in Transition*, Urbana, Illinois, pp. 276-284.

Wood, T.E.; Bormann, F.H.; Voigt, G.K. 1984. Phosphorous cycling in a northern hardwood forest: biological and chemical control. Science 223:391-393.

Zon, Raphael. 1927. Forest and water in the light of scientific investigation. In U. S. National Waterways Commission, Final Report. Senate Document 469. 62 Congress, 2d Session. V:205-302.