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FOREST HARVESTING AND WATER: THE LAKE STATES EXPERIENCE[1]

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ABSTRACT: The impact of forests on water has been a subject of argument for more than a century. It still is; and many studies conform that there is no single right answer in the debate. In the Lake States, clearcutting natural peatlands will not change annual streamflow nor will it seriously impact water quality if logging is done on frozen soils. However, clearcutting will cause water tables to fluctuate more, ranging from 9 cm higher to 19 cm lower than in peatlands with mature forests. Clearcutting upland hardwoods or conifers will increase annual streamflow by 9 to 20 cm (a 30- to 80-percent increase). Streamflow returns to preharvest levels in 12 to 15 years. Annual peak flows are at least doubled and snowmelt flood-peak increases may persist for 15 years. Water quality is not widely impacted, but operating logging equipment in stream channels will cause channel clogging by filamentous algae and loss of fish habitat. Permanent changes from forest to agricultural and urban land use on two-thirds or more of a watershed will significantly increase the size of flood peaks in the 2- to 30-year return interval storm or snowmelt.
(KEY TERMS: clearcutting; streamflow; forest fire; water quality; peatlands; wetlands; uplands; water yield.)

INTRODUCTION

"There is, perhaps, no other problem facing the American people today which demands such care in the scientific accuracy of its data and conclusions as does the relation between forests and water" (Raphael Zon, 1927). An overstatement? Yes; but in 1927, the previous half-century had seen the "Great USA Timber Harvest" sweeping from New England to the Lake States, the South, and the Pacific Northwest. Trees were needed everywhere for swelling cities; and stump fields, erosion, drought, and floods were recent memories that built anxiety and concern into America's second wave of immigration.

Raphael Zon, first Director of the Lake States Forest Experiment Station, made this statement in 1927 after 15 years of literature search that yielded some 1,200 references for his Senate Document No. 469: "Forests and Water in the Light of Scientific Investigation." These references were dated from 1801 with observations to 1789 and covered work in North America, Europe, the Romanov Empire of the Russias, and British Colonies in India, China, and Africa. It was Zon's intention "to bring together impartially all the well-established scientific facts in regard to the relation of forests to water supply" (Zon, 1927).

In 1927, the facts ("established with certainty") were (the answers in brackets are inferred by the author from the existing literature):

(1) The forest lowers air temperature inside and above it. [TRUE]

(2) Forests increase the abundance and frequency of precipitation. [usually FALSE]

(3) The destruction of forests affects the climate. [FALSE but TRUE for microclimates]

(4) In level country, forest transpiration drains marshy land. [mostly FALSE]

(5) In hill and mountain country, forests conserve water for streamflow. [usually FALSE, sometimes TRUE]

(6) Forests retard snowmelt. [usually TRUE, sometimes FALSE]

(7) Forests prevent erosion. [TRUE, to a point]

(8) Forests regulate the flow of springs (example: "The more direct evidence of the effect of [forest] clearing upon groundwater has been brought out by W. J. McGee, 1911. During a period of 22 years, 9,507 wells in. . .Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Ohio, Tennessee [sic], and Wisconsin show a lowering of. . .1.7 feet per decade or [by extrapolation] 13.8 feet for the 80 years since settlement began"). [usually FALSE, sometimes TRUE]

(9) The total discharge of large rivers depends on climate. [TRUE]

(10) Forests tend to equalize streamflow throughout the year by making the low stages higher and the high stages lower. [sometimes FALSE, sometimes TRUE]

(11) Forests cannot prevent floods produced by exceptional precipitation, but they can mitigate their destructiveness. [TRUE]

Zon was not alone in his consideration of forests and water. In 1928, Adolph Meyer, consulting engineer and Professor of Hydraulic Engineering at the University of Minnesota, revised his text: *The Elements of Hydrology*, first published in 1917. He states: "When flood producing rains

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fall on a watershed, cultural conditions, such as forest cover, have little effect in retarding the flow. [In fact], forests may contribute to floods by retarding the melting of snow as illustrated by the Little Fork River watershed] in northern Minnesota]" [TRUE and FALSE].

These two contemporaries, living in the same twin cities of Minneapolis/St. Paul, were both right and wrong. They drew many of their facts from observation supported afterward by reasoning from different premises. Theory was not fully developed and experimental testing was nearly nonexistent. The main lesson to learn from Zon and Meyer is that forest effects on water are not uniform. There is no single right answer. A second lesson is that there is much to learn between disciplines.

In non-fog-belts, clearcutting substantially increases streamflow (Anderson, *et al.,* 1976), but cutting Douglas fir in Oregon's foggy coast range will decrease annual streamflow because the trees' needles intercept large amounts of fog (cloud water) inducing fog drip (Harr, 1976). However, the cumulative effects of timber harvest activities, primarily clearcut logging in the transient snow zone in the western Cascades, have increased the size of snowmelt peak flows in the past 4 to 5 decades (Christner and Harr, 1982). Some engineering hydrologists, in contrast to Meyer's observations, agree that forests do affect peak flows, even from rain storms.

I recall Dr. Ven te Chow (Editor of the Handbook of Hydrology) telling his civil engineering hydrology class at the University of Illinois in 1964 about his consulting work on the Island of Oahu, Hawaii: "All my calculations of flood peak based on the rain, soils, and topography overestimated the measured flood peaks. I can only attribute this to the dense forests growing on the east side of Oahu." In Wisconsin, clearcutting followed by severe grazing can divert rain to overland flow because soil infiltration is reduced from 8 to 0.05 inches per hour (Stoeckeler, 1959); tilled land will similarly divert rain to overland flow and rob springs of infiltrated subsurface flow (Sartz, 1975). However, much of the observational correlations between forest harvest and the drying-up of springs from 1865 to 1915 can be attributed to a major wet-dry cycle in that half-century. "Springs near Wilmington, Massachusetts, dried up as a result of cutting pine forests. Where these were cut 20 to 30 years ago, springs have begun to flow again" (W. W. Cummings, Boston, Massachusetts, as reported in Zon, 1927). The long-term precipitation record for the New England States, however, shows a wet-dry cycle at a 5-year average high of 54 inches per year in 1868 gradually dropping to a low of 37 inches per year in 1909 with a subsequent rebound to a long-term mean of 45 inches (Meyer, 1928). While timber harvesting was often harked as the cause of drying springs, large-scale agricultural drainage in the Midwest contributed directly to lower water tables – by design. To add my own hearsay evidence, my grandmother often recounted summer days in the 1890's when she floated on a homemade raft down an east-central Illinois drainage ditch some 8 feet below the field surface. For more than a century our family has maintained this drainage system via taxes within a drainage district – typical of Midwest farming.

Climate and climate change are the long-term controls on streamflow, springs, floods, and droughts. Land use is secondary in importance to climate. The magnitude of land use impacts is a direct function of the area of land accumulating in various categories of use or condition. Area is the master variable in evaluating land-use imapcts on water, and determines our need to respond to impacts or not. Like flow from the faucet we forgot to turn off, forest harvesting affects water whether we are aware of it or not. Most effects go unnoticed; and others catch us on the wrong side of a road washout.

In this paper, I will briefly summarize forest harvesting and water in the Lake States. Our experience is longer, our tests are stronger, and perhaps (on this issue, at least) our emotion is less intense than those of a half-century ago, but surely another will read these words 60 years hence and point out where I was right and where I was wrong. This summary is divided into two parts – wetlands and uplands – and both will include a discussion of water yield (streamflow or recharge to ground water) and water quality. Tree harvesting by man or fire is the primary emphasis.

THE WETLANDS

Harvesting black spruce in strips from undrained peatlands or clearcutting an entire undrained peatland of black spruce does not change the annual amount of water flowing to streams leaving the peatland. Annual streamflow ranging from 5 to 20 cm (2 to 8 inches) of water is the same from forested or clearcut peatlands. Stripcutting of black spruce (100-foot-wide harvested strips alternating with 150-foot-wide forested strips) does not change the water table elevation in the harvested strips compared to the forested strips (Verry, 1981).

Clearcutting an entire undrained peatland (20 acres within a 60-acre watershed) did not change the average water table elevation, but it did increase the range of water table fluctuation. During wet, high water table periods, clearcutting causes water tables to rise as much as 10 cm higher than water tables under a mature forest, but during dry, low water table periods, the water table can fall 19 cm lower than such water tables (Figure 1). Clearcutting does cause greater water table fluctuation. In average precipitation years, there are no large changes in water table fluctuation. Water tables fluctuate most during years of high or low precipitation (Figure 2).

Increasing bulk density (and less pore spaces) with depth accounts for the greater water table departure during dry periods compared to wet periods. Elimination of canopy interception can explain the higher water levels during wet periods. Harvesting the trees adds 30 percent more precipitation annually to the bog surface by eliminating tree interception (Verry, 1976). Greater evapotranspiration during dry periods can be explained by changes in wind, solar radiation, surface temperature, and proliferating herbaceous plants after tree harvest.

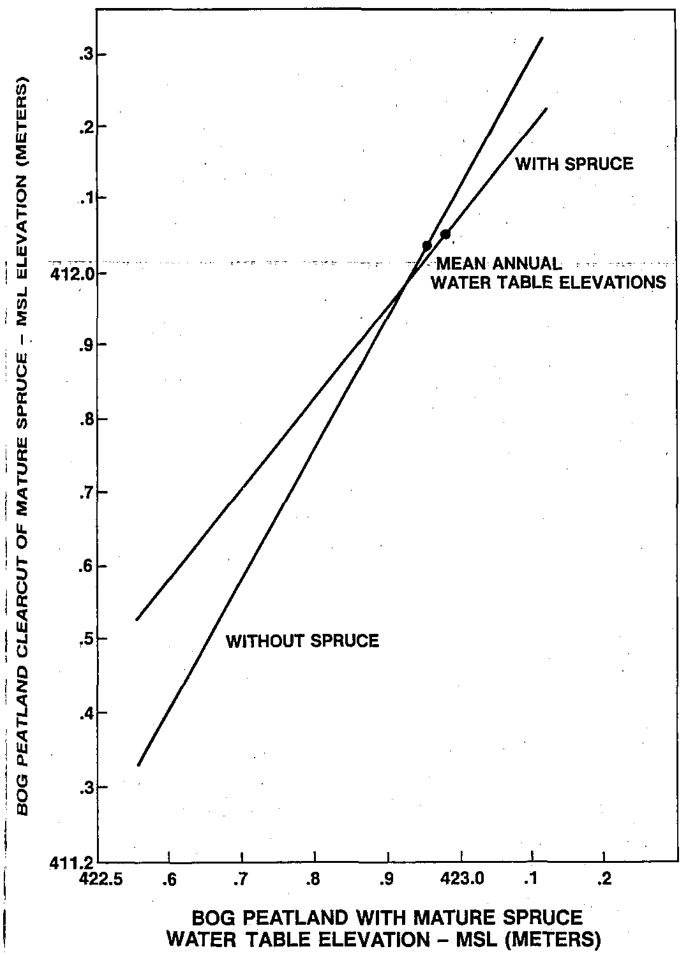

Figure 1. Water Tables in Bogs Clearcut of Spruce Range Lower and Higher Than in Forested Bogs.

Wind at the open peat surface is 4½ times greater than at the peat surface under trees. A portion of solar radiation striking mature trees goes into sensible heat, heating the trees and the air around them while this portion of solar radiation striking the open peat surface (with a near surface water table) goes into the evaporation and transpiration of water. Because of this different sink for energy, tree canopy temperatures are 4 to 7°C warmer than open peat surfaces (Brown, 1972b). Finally, grass biomass and sedge biomass increase nearly five times the first growing season after clearcutting; these plants transpire readily compared to mature spruce trees, which have a high internal resistance to water flow (Brown, 1972a, 1973). The water table fluctuates less in fens than in bogs because of large amounts of inflowing ground water.

Does harvesting trees in peatlands change water quality? Yes. Again, bogs and fens differ because there is less water flow in bogs, and because prescribed slash burning accompanies harvesting in fens to set back the heavy alder brush found there and to allow competition-free seedling growth for several years (Johnston, 1977). Phosphorus is the nutrient of primary concern in waters leaving a clearcut (or clearcut/burn) area because large amounts of that nutrient will cause algae blooms in lakes. Phosphorus from clearcut bogs or clearcut and burned fens is increased for one to several years after harvest. This results from the warming of the soil and increased microbial activity that breaks down phosphorus-rich organic matter. Although relative phosphorus production may triple the first year, it declines to near preharvest levels in 1 to 4 years (Table 1, Knighton and Stiegler, 1981).

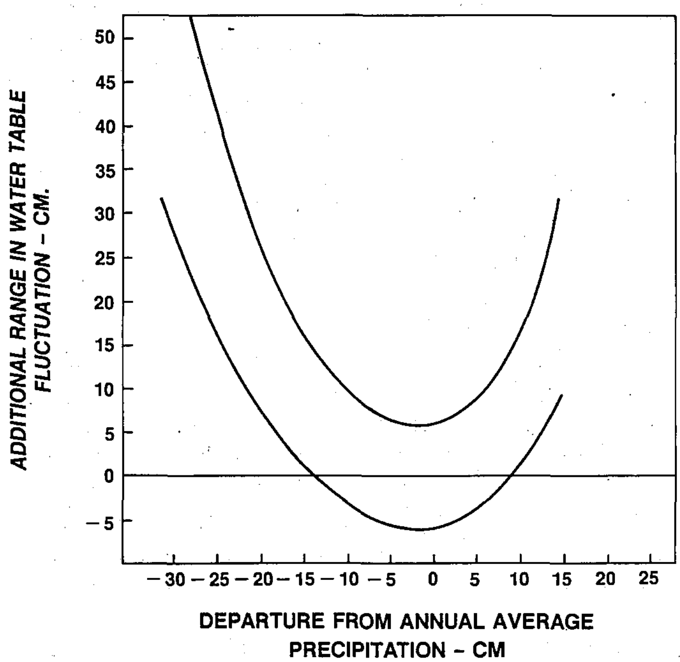

Figure 2. The Increase in the Range of Water Table Fluctuation in a Bog Clearcut of Mature Spruce is a Function of Departure from the Annual Average Precipitation (the lines enclose an envelope of response).

TABLE 1. Estimated Total Phosphorus Released After Harvest on a Bog and After Harvest and Burning on a Fen (kg/ha of peatland/yr).

Peatland	Preharvest	Years Since Harvest 1	2	3	4	5	6
Bog	0.33	0.89	?	0.35	0.37	– –	– –
Fen	0.71	2.18	1.03	1.77	0.79	1.11	1.05

If we assume a watershed area to lake area ratio of o:1, a mean lake depth of 4.6 m (15 ft), and the worst condition of the first year after clearcutting and burning a fen, it would require a harvested area equal in area to the lake (and immediately adjacent to the lake) to approach algal bloom conditions. For bog harvesting, it would require a harvested area 2½ times the lake area. Because these conditions are rarely met, the phosphorus contribution to lakes from peatland tree harvesting is not significant. These interpretations assume that tree harvesting on peatlands is done on frozen soils, and that equipment does not cut into and mix organic soils. Warm-weather mixing of organic soil can substantially increase phosphorus export.

The concept that harvesting trees causes streamflow to increase and water tables to rise (in contrast to the studies reported above) derives from well-documented studies on mineral soils (Hibbert, 1967). Confirming tests of this hypothesis have been made in high water table areas with both mineral and organic soils (Trousdell and Hoover, 1955, and a review by Predmore and Brooks, 1981). However, all these studies have been on soils where the water table existed near the surface only briefly, usually during the spring. Because the areas *were drained* or naturally had a water table at 30 cm (12 in) or more below the land surface during the growing season, the hydrologic response to harvesting trees was tied to the influence of an *unsaturated* soil profile. Results from these studies on drained soils also typically show the water table to rise and streamflow to increase after tree harvest.

In summary, forest harvesting *on organic soils*, as commonly done in the Lake States, does not change water yield or significantly increase nutrient yields; but because it does cause greater fluctuation in the water table, nursery seedlings should be placed in the bottom one-third of the distance between hollow bottoms and hummock tops to avoid desiccation or flooding. Results of the controlled hydrologic studies reported here contradict many other studies reported in the literature, both for wet organic and mineral soils. Why the contradictions?

The existence of an unsaturated soil profile of 30 to 300 cm (12 to 120 inches) in other studies provides a mechanism for water to pass beneath the strong influence of radiation and wind. Thus, the hydrologic response depends on the time water is available near the soil surface. When trees are cut from a drained soil, additional water (previously intercepted) can move through the profile quickly and become unavailable to evapotranspiration. Deep roots retrieve part of this water for transpiration, but most root systems are shallow in peatlands. The depth of unsaturated profile required appears to be about 30 cm (12 inches). With water tables above this depth, the type of vegetation affects hydrologic response only on a short-term basis. Below this depth, tree harvesting can yield more water to underground storage and streamflow. When Urie (1977) calculated ground water yields under hardwood and pine forests on deep sands in Michigan with and without a high water table, he found that the presence of a deep unsaturated zone produced more water yield than a soil saturated nearly to the surface.

THE UPLANDS

Water Yield and Quality

Most upland soils have an unsaturated zone of a few to tens of meters. Upland soils can pass water from snowmelt or large rains (> 2 cm) beneath the rooting zone of forest trees (2.5 m) or quickly pass it as saturated, subsurface flow to streams, usually during spring thaw and late fall recharge periods. Vegetation changes are reflected in the yield of water to deep seepage (ground water) or streamflow. In nearly every case, water travels to a stream by either deep seepage to a ground water flow net, or by rather shallow subsurface flow (at 15 to 45 cm deep over the top of B horizons). Surface runoff is rare on forested land or clearcut land with the forest floor intact.

The extra amount of water passed to ground water or streams after harvest is a function of: 1) the area cut as a percent of a given watershed, 2) the species of tree harvested, and 3) the density of the stand harvested. Area is the master variable in evaluating land-use impacts, and harvesting trees is no exception. Bosch and Hewlett's (1982) review of experimental catchment studies confirms that water yield increases, although real at the site of cutting, are not detectable if less than 20 percent of a watershed is harvested. This results from a large edge effect relative to the cut area, and our inability to accurately measure water yield changes of less than 2 cm (1 inch) on a total area-depth basis.

Clearcutting aspen in Minnesota will increase streamflow by 9 cm (3.5 inches) on the clearcut area (Verry, 1972). If a new aspen stand regenerates, it will take 12 to 15 years before this initial increase of 9 cm is reduced to zero. No whole-watershed experiments in the Lake States have tested the impact of cutting upland conifers on streamflow. It has been estimated, however, from studies of rain and snow interception in aspen and red pine forests that for forests of equal basal area (23 m^2/ha or 100 ft^2/acre), clearcutting pine forests will yield an additional 7 cm (2½ inches) above the 9-cm increase obtained by clearcutting aspen forests (Verry, 1976). Evapotranspiration differences may add to or interact with interception differences, but they have not been directly quantified. Across much of the Lake States, these increases in water yield represent a 30- to 80-percent increase in either streamflow or recharge to ground water (Table 2). The importance of stand density on water yield has not been directly assessed for hardwood species, but thinning of pines is estimated to cause a streamflow increase. Furthermore, clearcutting low basal area density conifer stands would cause less of a streamflow increase than clearcutting high basal area stands (Verry, 1976; Urie, 1971).

Under reasonable conditions of timber sale layout, where logging on heavy soils during wet conditions is avoided and riparian areas are logged carefully, clearcutting on upland sites does not adversely affect water quality (Verry, 1972). However, skidding in stream channels (where tires grind organic matter and bank soils into a slurry of readily available nutrients) will cause filamentous green algal populations to explode, clogging channels and usurping trout habitat (personal communication, Bonnie Ilhardt, Hydrologist, Chequamegon National Forest). In-stream tree trunks from the natural death of riparian trees provide channel stability and induce pool and riffle habitat, but excessive logging debris in dry channels in August block April spawning runs when these same channels flow two feet deep. Although most harvesting does not change the concentration of nutrients in water, harvesting does increase the total flow of water by 30 to 80 percent from a given site and thus the total flow of nutrients by water from the site is also increased by 30 to 80 percent. These may be important amounts to consider when site nutrient loss is charged against future forest growth.

TABLE 2. Estimated First-Year Increases in Water Yield After Clearcutting of Aspen and Pine Forests in the Lake States (Verry, 1972, 1976).

Basal Area Stocking		Increase in Water Yield After Clearcutting*	
m²/ha	ft²/acre	cm	inches
	ASPEN		
23	100	9	3.5
	PINE		
10	43	12	4.6
20	87	15	5.8
30	130	18	6.9
40	172	20	8.0

*These increases reduce to zero over a 12- to 15-year period during growth of a new aspen forest (perhaps 20 years for pine forests; Fox, 1984). Average water yield in the Lake States ranges from 13 to 2 cm under mostly mature aspen or hardwood conditions.

Wind and fire will lay down and consume trees as surely as the chainsaw and shear. Do these events change water yield and quality, too? Absolutely. The best account of these forces was documented under paired watershed conditions at the Experimental Lakes Area (ELA) in Ontario some 160 km (100 mi) north of International Falls, Minnesota/Fort Francis, Ontario. A series of catastrophes one year apart (1973, 1974, 1975) confirmed that a severe wind storm (85 percent of the trees leveled), an extremely intense fire (all soil organic matter mineralized 3 cm into the mineral soil), and a repeat fire a year later caused streamflow increases of 23, 17, and 14 cm (9.0, 6.6, and 5.5 in) the first three years after the first catastrophe (Schindler, *et al.*, 1980). The ELA watersheds supported commercially mature stands of jack pine and 80- to 100-year-old upland black spruce. These values are similar to those estimated in Table 2 for pines.

In contrast to clearcutting aspen, these catastrophes of wind leveling and severe fire caused a doubling in total nitrogen in streamflow on the basis of increased flow and increased concentrations. This doubling in total yield was also observed for total phosphorus and potassium. The increased flow and increased concentrations, however, were short-lived, taking only three growing seasons to return to prewindstorm conditions. There is little soil on the bedrock of the ELA; thus, there is little of an unsaturated zone and less yet of an unsaturated storage zone below tree roots.

Neither the wind damage nor the severe fires caused detectable nutrient increases in an adjacent lake. Thus, lake eutrophication from upland tree removal alone is not a serious concern. Similar conclusions were reached regarding the Little Sioux Fire in northeastern Minnesota (Wright, 1976; McColl and Grigal, 1975, 1977).

The water yield increases measured for a given clearcut area can be large – 30 to 80 percent (and usually water quality impacts are minor if machinery is kept out of stream channels), but the picture changes if we look at large areas. Within the forested region of the Lake States, about 2 percent of the stands are harvested each year and only a few of the stands are converted from hardwoods to pines. Thus, for large areas of forest land (say, the Prairie River watershed in Minnesota, the Brule River watershed in Wisconsin, or the Au Sable River watershed in Michigan), under present-day land-use restrictions and even under ambitious harvesting and conifer planting programs, it is unlikely that annual streamflow from large watersheds could be changed by more than 5 percent (Bernath, *et al.*, 1982).

FORESTS AND FLOODS

Rain Storms

Clearcutting aspen forests with subsequent sucker regeneration will double the size of rain-produced peak streamflow rates the first 2 years after harvest and will increase the volume of stormflow by a factor of 2. The increase in volume response is reduced to preharvest levels in the third year, but rain storm peak flows remain at 2 X levels for at least 5 years after harvest. These increases are likely due to an increase in soil water and a concurrent decrease in available storage volume in the clearcut area (Verry, 1972). Real changes occur in the magnitude of rainfall-runoff peaks as a result of harvesting. For the average annual rainfall-runoff peak (a 2-year recurrence interval), the peak rate changes from 7 cubic feet per second per square mile (CSM) with mature forests to 12 CSM after harvest; the 10-year recurrence interval storm has a runoff peak rate changing from 19 to 51 CSM (Verry, *et al.*, 1983). Clearcutting aspen forests within the context of a large region where forests are dominant will not affect rain-caused flooding in large watersheds because the effect is short-lived and because aspen clearcutting on a sustained yield basis would not occur on more than 2 to 3 percent of the area in any given year. If extensive clearcutting occurs, culvert sizing should be considered to reduce the occurrence of road washouts (see discussion below on snow, as the peak rates of flow from either snowmelt or rain are similar).

Snowmelt Peaks

The size of snowmelt peak discharge is a function of energy availability and the amount of snowpack water equivalent on a watershed. Based on measured observations in forest soils (Verry, 1972), the following sequence of events will cause snowpacks to produce floods regardless of the presence of forests:

1. Fall soil water deficit (available storage) is less than 8 cm (3 in).
2. Winter snowpacks accumulate more than 20 cm (8 in) of water equivalent.
3. At least one night temperature after the onset of melt stays above freezing followed by a day temperature over 16°C (60°F).
4. The melt rate will increase if the humidity stays near 100 percent during the day (a foggy day).

Energy and energy distribution are the driving forces that cause snowmelt flooding when water storage is satisfied and water supply in the form of snowpack is present. Solar radiation provides a significant input, but convection of warm air masses from the Gulf of Mexico or the Southwest is the primary vector for moving heat into the region. Condensation during misty, foggy days also adds significant heat to the snowpack surface. Forest harvest and aspen suckering can also interact to redistribute energy and impact snowmelt flooding.

Clearcutting aspen will at least double peak streamflow rates resulting from snowmelt, but snowmelt runoff volumes for the entire melt period remain the same. The peak flows occur 5 days earlier after harvest than they do from mature forest areas. These higher and earlier snowmelt-induced peaks persist longer after harvest than the rain-induced peaks do. They have been measured at 2.4 times higher nine years after harvesting, and this effect may persist as long as 15 years after harvest (Verry, *et al.*, 1983). The mechanism that drives this effect is again a redistribution of energy. It is theorized (Verry, *et al*, 1983) that solar radiation is absorbed by the tens of thousands of leafless sucker stems (per acre) and reradiated as longwave radiation to the snowpack. Mature trees with crowns 12 to 25 m (35 to 75 ft) above the ground greatly reduce the strength of this reradiation so that advected warm air masses are the primary source of energy to snowpacks under mature canopies. Young stands (less than 15 years old) add considerable longwave radiation energy to the snowpack in addition to that added by advected warm air masses.

Because there is a five-day difference between peak snowmelt flows in clearcut (or within 15 years of clearcutting) and older stands, harvesting will desynchronize snowmelt within a forested area and actually reduce flood peaks by 30 percent when a mosaic of young and older stands exist in the same area. A generalized hypothesis of the effect of clearcutting on snowmelt peak flow (flood peak) is shown in Figure 3 (Verry, *et al.*, 1983). If a large clearcut drains to a single road culvert, clearcutting will increase the need for a larger diameter culvert and the probability of road washout (Table 3).

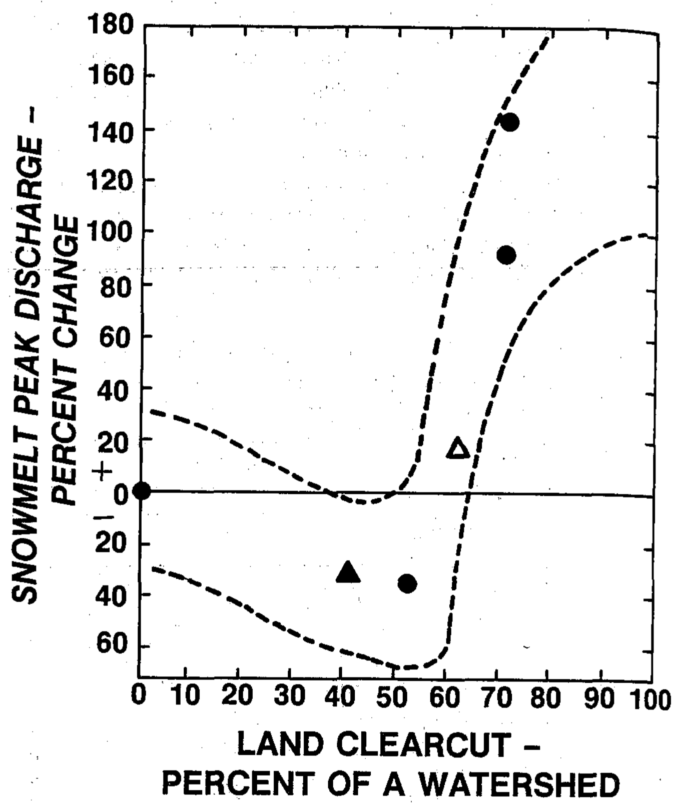

Figure 3. Relation Between the Portion of a Watershed Clearcut (with regrowth for 15 years) and the Change in Snowmelt Peak Discharge Size Compared to Mature Aspen Forest Conditions. Lines hypothesize an envelope of response for Lake State conditions. Circles are measured values from controlled experiments. Triangles represent conditions in the Upper Mississippi River Watershed (measured at St. Paul, Minnesota) when European settlement began (▲) and in 1977 (△).

TABLE 3. Effect of Continuous Clearcutting on the Need for Culvert Capacity and Size.

Area of Continuous Clearcut Draining to a Culvert		Stand Age			
		16 Years to Maturity		Clearcut to 15 Years	
Hectares	Acres	Maximum CFS*	Culvert Size (inches)	Maximum CFS*	Culvert Size (inches)
16	40	2	15	3	15
32	80	4	18	6	24
65	160	8	24	12	30
130	320	15	30	25	36
260	640	30	36	50	48

*Cubic feet per second of peak runoff measured from 1960-1985. Based on streamflow records at the Marcell Experimental Forest (north central Minnesota) and reported increases (Verry, 1972; Verry, *et al.*, 1983).

The Big Picture

Harvesting and regenerating trees within a forested area will generally not cause large changes in peak flows for large areas. However, harvesting trees and converting land to pasture or crops will cause permanent changes in streamflow and sediment yield if soil cultivation or heavy, continuous grazing is an annual feature of land use (Sartz, 1978). Basically, soil covered with vegetation and vegetation debris infiltrates most rainfall, which then passes to water tables, springs, and streams, but cultivated soil or heavily grazed, compacted soil is less receptive to infiltration and promotes overland runoff and erosion (Sartz, 1975). Forests, abandoned hayland, or moderately grazed pasture will all promote infiltration. Surface runoff from tilled land is as much as ten times that from vegetatively covered land and may produce 100 times the amount of sediment. In general, forest land produces low sediment yields of less than 0.62 t/ha/yr (0.25 tons/ac/yr) (Patric, *et al.*, 1984).

One of the longest records showing the impact of large-scale land-use change on flood peaks is the harvest of forests and permanent conversion to agricultural land in the Upper Mississippi River measured at St. Paul, Minnesota. This watershed containing 95,300 sq. km (36,800 sq. mi) includes the Minnesota River as well as the main stem of the Mississippi. Before European settlement, the watershed was 61 percent forested, but by 1977, conversion to agricultural and urban land use had reduced the portion of forested land to 34 percent (Figure 4). Most of the forest harvesting took place from 1869 to 1910 (Steer, 1948), but much of the watershed had been logged for hardwoods and pine and burned over by 1899 (Ayres, 1899). Peak lumber harvests in Minnesota occurred in 1899 when 2.3 billion board feet were sawed and shipped to expanding cities like Chicago, St. Louis, and St. Lawrence ports.

The harvesting, burning, conversion to farming, and abundant second-growth suckering probably reached its greatest impact on flood flows 10 to 15 years later following the energy redistribution cycles outlined by Verry, *et al.* (1983). Based on their "percent of land clearcut" model (Figure 3), the Upper Mississippi should have experienced a 65-percent increase in the magnitude of flood peaks beginning about 1910 that persisted because land-use changes were largely permanent. Miller and Frink (1982) analyzed annual flood peaks on the Mississippi River at St. Paul and compared them with annual flood peaks on the Red River of the North at Grand Forks, North Dakota, in a thorough evaluation of drainage practices in the Red River Basin. Drainage ditches installed in the Red River Basin during the late 1800's and early 1900's were not led to regional drains and made almost no impact on Red River flooding; but Miller and Frink's data, when replotted to use the Red River as a "control" and interpreted in terms of land-use change on the Upper Mississippi, show a significant increase in annual flood peaks at St. Paul in 1908.

The increase in annual flood peak is 43 percent (Figure 5), about 20 percent less than that predicted by the "percent of land clearcut" model, but that model has no provision for channel routing and the predicted effects vary substantially in the 50 to 70 percent clearcut area range. Also, in some areas, conversions from forest to open land resulted in a 50/50 mixture that would actually reduce flood peaks.

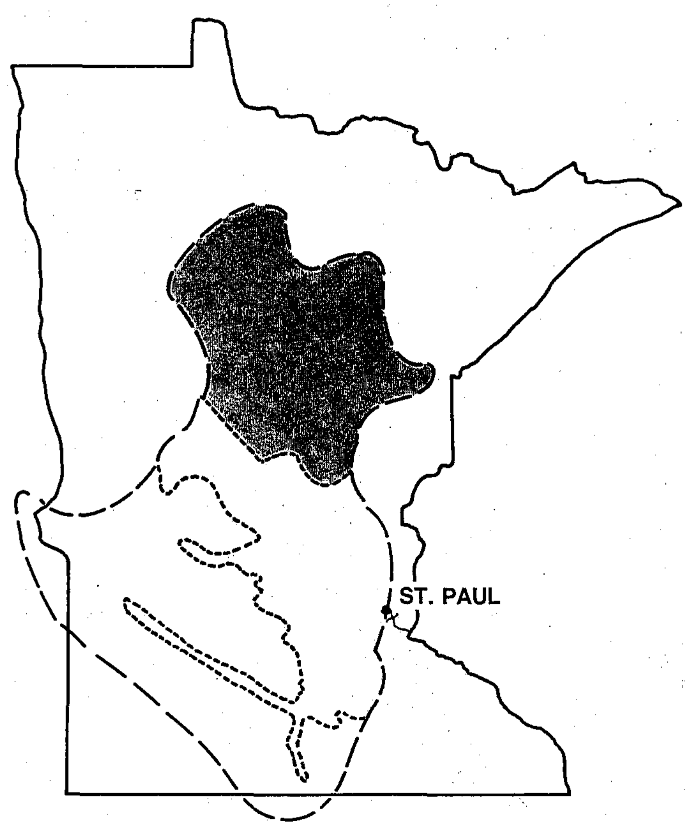

Figure 4. The Occurrence on the Mississippi River of Predominantly Forest Land in the Upper Mississippi River Basin (long dashed boundary) Before European Settlement (north of the short dashed line – 67 percent) and in 1977 (dark shading – 34 percent).

In other large rivers in the Lake States where forest land is permanently converted to open land, open land may exceed two-thirds of the watershed and then we should expect average annual, even 10- and perhaps 30-year recurrence interval flood peaks to increase by 50 to 100 percent. This increase is most likely where snowpacks persist throughout the winter. Where snowpacks regularly experience accumulation and melt cycles throughout the winter, single accumulations rarely reach the 8 inches of water equivalent required to produce significant floods; but the principles of quick-melt still apply when snowpacks do reach that level.

Raphael Zon and Professor Meyers were right in that emotional era concerning forests and floods at the turn of the century: "Floods which are produced by exceptional meteorological conditions cannot be prevented by forests, but without their mitigating influence [most pronounced in the

2- to 30-year return intervals], the floods are more severe and destructive" (Zon, 1927).

Studying the history of our nation and evaluating controlled experiments sharpens our understanding of forests and water. It was no accident between 1890 and 1910 that springtime in the Lake States produced river flows sufficient to float 2 billion board feet of logs to downstream mills. Harvest trees, reap water!

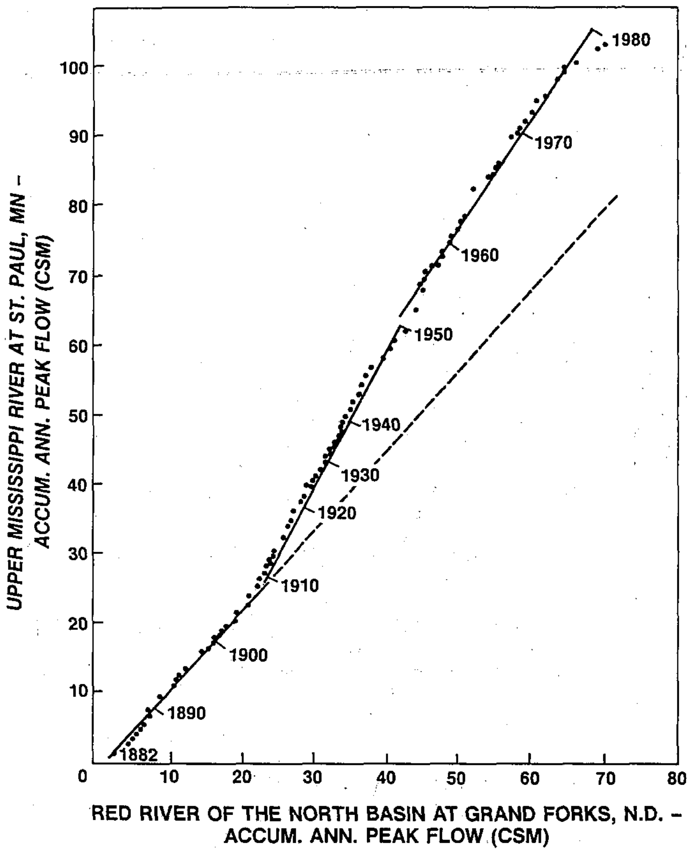

Figure 5. Annual Peak Flow on the Mississippi River at St. Paul, Minnesota, Increased Approximately 43 Percent in 1908 Coincident with the Conversion of Native Forests to Agricultural or Young Forest Land (stands less than 16 years old). Redrawn from Miller and Frink (1982).

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