FORESTS AND WATER.
effects of forest management on floods, sedimentation, and water supply

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CONTENTS

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From the background of more than 100 years' collective experience in watershed research and from comprehensive review of the literature of forest hydrology, the authors summarize what is known about the forest's influence on the water resource, particularly the effects of current forestry practices. They first examine the fundamental hydrologic processes in the forest. They then discuss how water supply, floods, erosion, and water quality are affected by timber harvesting, regeneration, tree planting, type conversion, fire, grazing, and the application of fertilizers and pesticides. They consider and present the special problems of fire-prone chaparral, phreatophytes, wetland forests, and surface-mined sites. Finally, they assess potential increases in water yield that might be achieved by forest management in each of six major forest regions in the United States and venture some predictions about future management of watersheds. Nearly 600 references provide a fairly comprehensive overview of the literature.

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Relationships between forest and water—both imagined and real — have played an important part in the conservation movement. In Europe these relations were recognized as early as the 13th century. In the United States they were embodied in 19th century legislation to conserve the forest. In 1876, concern for water motivated the first attempt by Congress to create national forests from public domain in the West: "for the preservation of the forests of the national domain adjacent to the sources of the navigable waters and other streams of the United States," and to determine what should be reserved in order to prevent such rivers from becoming "scant of water." Legislation early in 1897 for reservation of forested public lands was followed the same year by an act that specified their water-control as well as timber-supply functions: "no public reservation shall be established except to improve and protect the forest within the reservation or for the purpose of securing favorable conditions of water flows and to furnish a continuous supply of timber."

The ascribed roles of the forest in relation to water were employed even more strongly to justify the purchase of 23 million acres of forest lands in the East for national forests. Out of this effort, but not without considerable controversy, came the 1911 Weeks Law that provided "for the protection of the watersheds of navigable streams and to appoint a commission for acquisition of lands for the purpose of conserving the navigability of navigable rivers." At question, both before and after passage, was the thesis that streamflow is regulated by the forest. Conservationists taking the affirmative side had little more to offer for justification than observation and intuition; engineers, in opposition, had no better argument than some exceptions to observations and a strong disapproval of the intuitive approach. No firm data were available to support either side.

Obviously, the subject required research, and in 1909 the first forest watershed study in the United States was started at Wagon Wheel Gap, Colorado. Increasing flood damage throughout the next two decades kept the forest and flood issue alive. In the early 1930's, the U.S. Forest Service started additional research at the San Dimas Experimental Forest in southern California, the Sierra Ancha Experimental Forest in central Arizona, and the Coweeta Hydrologic Laboratory in western North Carolina.

Before many results were forthcoming, however, the Omnibus Flood Control Act passed in 1936 gave the Forest Service responsibility "for conducting flood control surveys on forested watersheds to determine the measures required for runoff and water-flow retardation." Of necessity research programs were expanded, and in the 1940's their results began to set forth the forest's influence on water yield, floods, and erosion. Out of this research came two salient conclusions: (1) forest cutting and forest growth can have a major influence on water yield; and (2) the forest, because of its full occupancy of site, provides the maximum opportunity for controlling runoff from flood-producing rainfalls; even so, the forest cannot prevent all floods.

By the 1950's watershed management research divisions had been established at all nine Forest Service Experiment Stations. By the 1960's the number of forested experimental watersheds under study reached 150. By 1970 almost 2,000 papers had been published describing results of research on watershed management. In addition, courses in forest influences, forest hydrology, or forest watershed management were being offered at 25 of the 32 accredited forestry schools (Sopper 1970), two textbooks had been published, and two international symposia in forest hydrology had been held.

Out of this growing body of knowledge about the forest's influence on streamflow came a new subject matter in forestry; namely, forest watershed management. Legal recognition came in the Multiple-Use Sustained-Yield Act of 1960, which authorized the establishment and administration of national forests "for outdoor recreation, range, timber, watershed, and wildlife and fish purposes."

In the 1970's there is growing awareness of the forest's influence on water yield, floods, and water quality. Water shortages are becoming prevalent and threaten to become more so, when flood damages have reached new peaks, and when pollution of water supplies is causing increased concern.

Knowledge about relationships between forestry and water has been greatly enhanced during the last three decades. This report summarizes and evaluates research evidence and other information pertinent to the forest's influence on water, especially on how this influence can be managed for man's benefit so as to increase water yield, reduce floods, and improve water quality.[1] Though we hope our summary will be useful to fellow forest hydrologists, our principal aim is to provide students, practicing foresters, and other professionals an insight into current knowledge of relations between forestry and water. These persons need help in water supply management because of present and predictable increased pressures on forest land and the emphasis today on multiple use of these lands. We make no claim that the findings reported here or our interpretations of them is a basis for any management decision. Management is site specific and the research results were site specific. But since sites are generally different, integrating sites and management is a task for professionals.

After that brief introduction, this report (1) discusses the hydrologic processes that govern the movement of water in the forest, (2) considers forest treatment and water, the effects of management practices and other agents on the water resource; and (3) discusses some local and regional extreme situations. Next, the paper discusses generally the potentials for management — first with respect to water yield, floods, and water quality; then it presents the possibilities for improving hydrologic management in three regions in the East and three regions in the West. Finally, the report assesses the place of forestry and water in tomorrow's society.

In reporting quantitative results we have retained common U.S. rather than metric units to avoid problems of duplicate numbers and problems of significant figures, and because we still "think" in nonmetric units.

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[1] Forestry is the science, art, and practice of managing forest lands and their natural resources. Since the dividing line between forest and nonforest is often hazy, precise definition is not easy. The term "forests," as used herein, includes all tree and shrub lands where canopy cover is greater than about 15 percent of the land surface.

I - HYDROLOGIC PROCESSES

Forestry and water are inseparable. Forests and water occur together and they interact. Plant a tree and it will use water; cut a tree and its water use ceases. Trees mark where water is: the greater water-providing regions of the United States are largely tree-covered. These forests require a minimum of about 20 inches of water per year but use much more than that if it is available. Water in excess of this use penetrates the permeable forest soil to underground storage and streamflow except for a small amount that evaporates from the forest floor or snowpack. Water released from the forest is generally a beneficial component of the water supply needed by man, but occasionally an excess of water from forest lands contributes to damaging floods.

The wide range among forest types in the United States, in the amount of precipitation they receive and in the quantity of streamflow they yield *(fig. 1)*, complicates the evaluation of the hydrologic processes in forests. (The maps here show only the conterminous United States; if Alaska and Hawaii were included, the range would be even greater.)

The circulation of water from the seas to the atmosphere, to the ground, and back to the seas, is called the "hydrologic cycle." This cycle can be considered a system of water-storage compartments (the atmosphere, the soil mantle, the stream, etc.) and the flows of water (either solid, liquid, or gas) within and between them *(fig. 2)*. We call these individual storages and flows "hydrologic processes." Division of the cycle and the naming of its components make it easier to study how water and energy enter the system, and how they are stored, lost, and delivered. We hope, too.

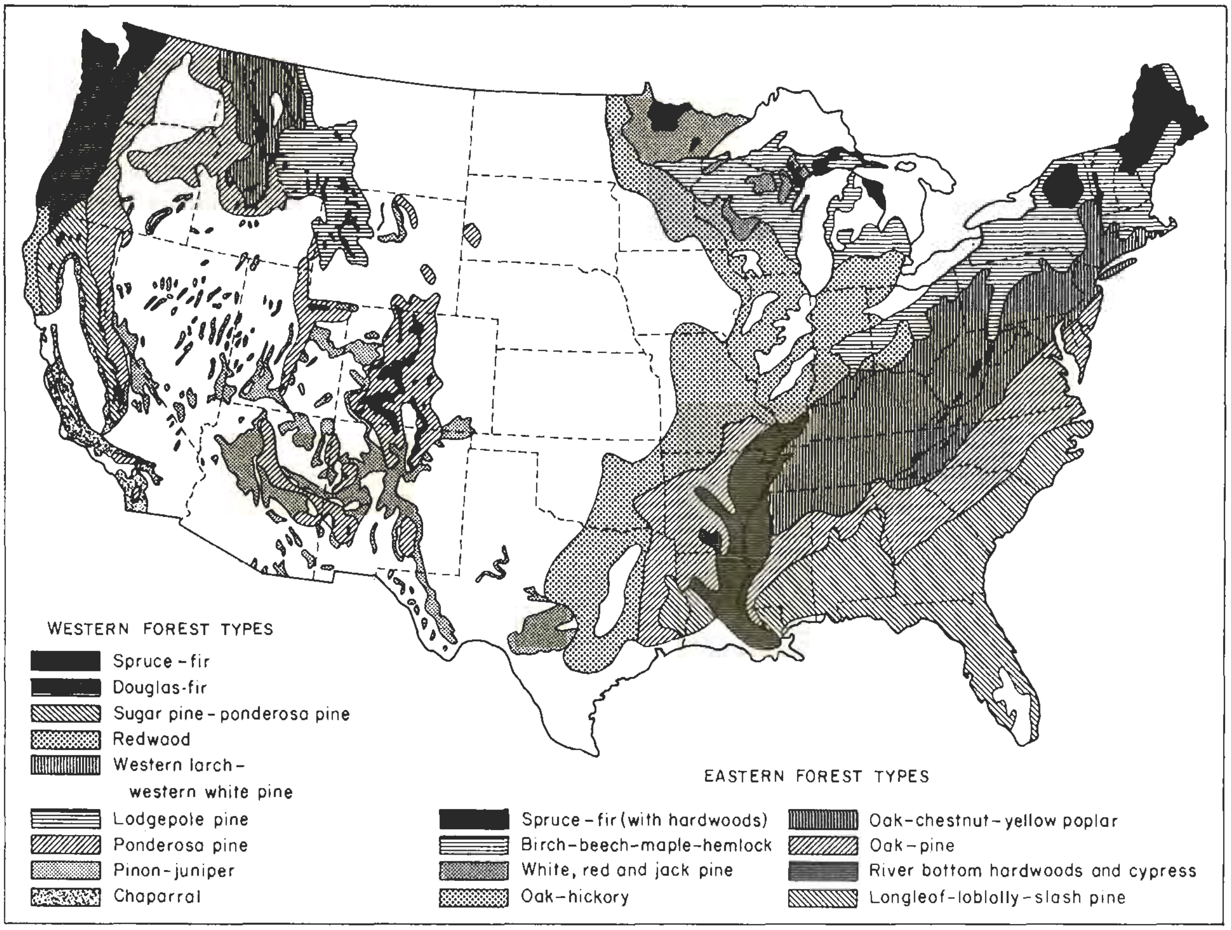

Figure 1-A—Major forest types in the Western United States consist chiefly of softwoods; in the Eastern United States, the major types include both softwoods and hardwoods.

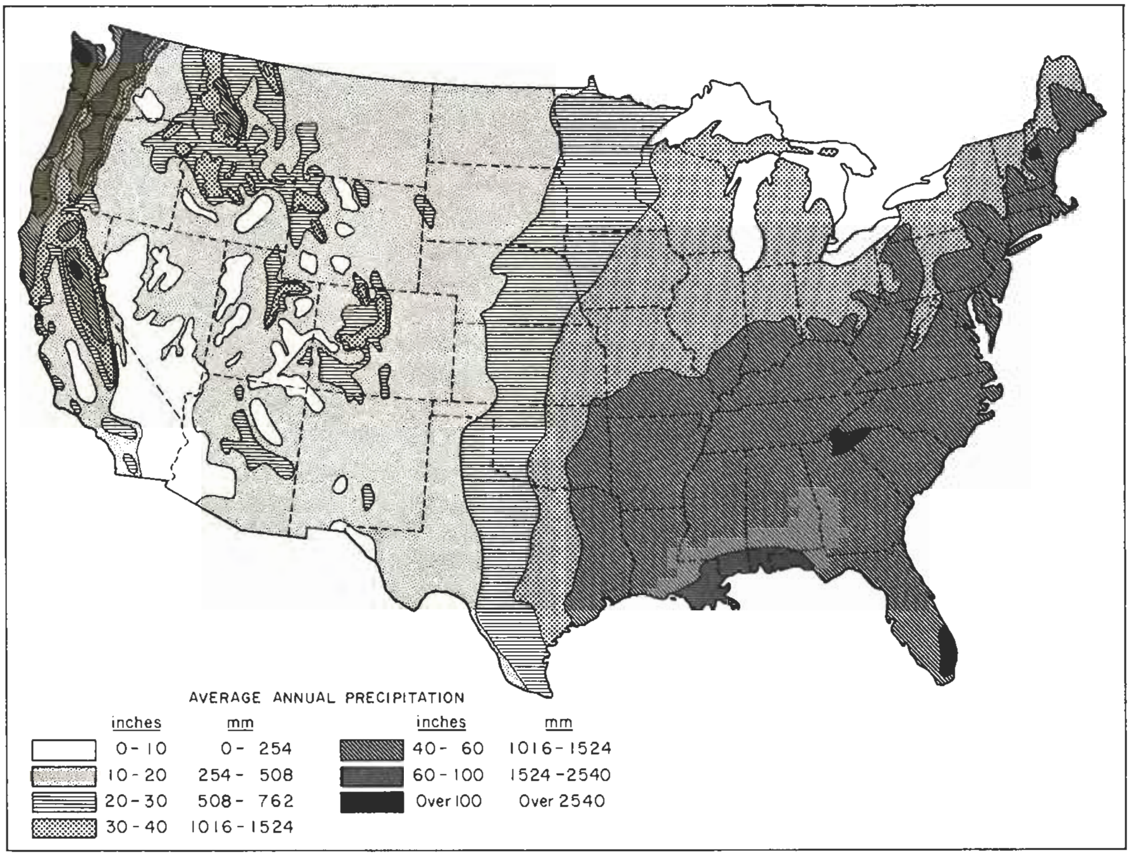

Figure 1-B—Average annual precipitation in the conterminous United States ranges from less than 10 inches to more than 100 inches.

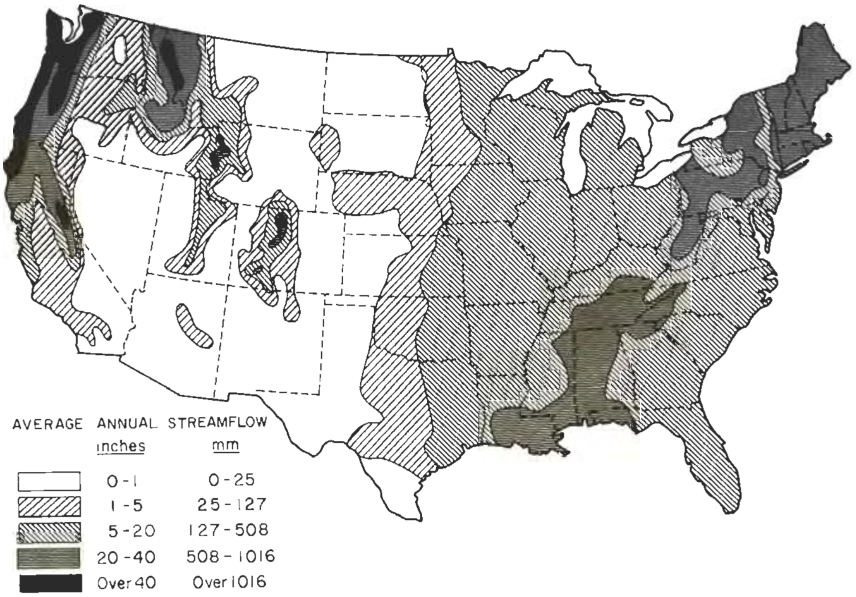

Figure 1-C—Average annual streamflow in the conterminous United States range from less than 1 inch to more than 40 inches.

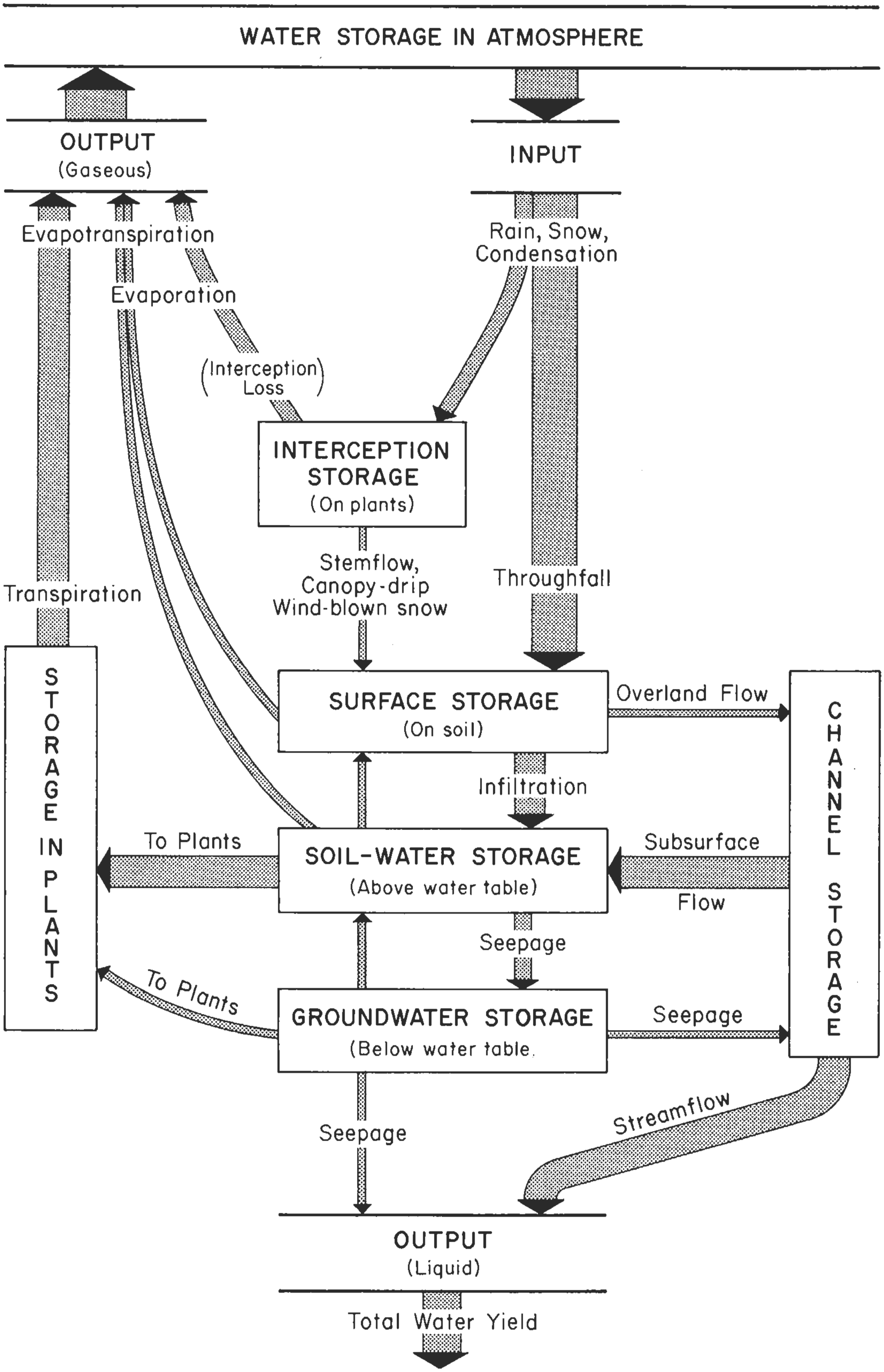

Figure 2—The hydrologic cycle consists of a system of water-storage compartments and the solid, liquid, or gaseous flows of water within and between the storage points.

that the processes are additive so we can predict water supply, floods, and water quality by summing the data on the individual processes.

Measurements of individual processes are subject to considerable error, biases, and faulty criteria of evaluation. In reporting their results, researchers usually have not worried much about rejecting a hypothesis when it was proved to be true (Type II Error); they say, "The differences were not significant." The results reported here, then, require further scrutiny by the user; this report is essentially an introduction.

Hydrologic processes are usually studied in what appears to be their logical time sequence, such as the inputs from precipitation, interception by vegetation, surface storage and flow, subsurface storage and flow, groundwater flow, and streamflow. Of course, each of these processes may be subdivided; for example, precipitation, the first phase of the hydrologic cycle, may be subdivided into rain and snow. Our understanding of hydrologic processes has improved by study of the energy relations that affect them; for example, the energetics of rainfall impact on the soil, the effects of solar radiation on snowmelt, and the sources of energy required to evaporate water. Each hydrologic process in the forest ecosystem is influenced by the type, size, age, and arrangement of trees. Forest units are highly diverse, and this complicates their management for water as well as for other goods and services. How precisely has the forest hydrologist determined the relations between water and the forest? Let us examine the evidence.

Hydrology in the Forest

The conditions under which the forest functions hydrologically differ greatly in time and space. Forest types and stand conditions, forest soils, and even forest topography have developed from diverse parent geologic material through a long succession of tectonic events, variable climate, and sequences of other violent natural events. One 40-acre tract may perform like another 40 acres, but probably not like the 40 immediately above or below it on the slope, or like the one on the facing slope. And each tract may perform differently from all others.

The hydrologist seeks quantitative measurements of each process, the conditions that influence each, and of the interactions between processes. He uses relationships derived from these data to predict the performance of the processes in other areas where he can determine the conditions that control them. The result is a series of estimates ranging from distribution of rainfall and snowfall, through the role of energy in the water balance, to the flow of water within and out of the forest areas under consideration.

This report updates the knowledge of processes that was so well documented by Kittredge (1948) in *Forest Influences,* Geiger (1965) in *The Climate Near the Ground,* and Molchanov (1963) in *The Hydrological Role of Forests.* What have we learned in the years since these texts were published? Forest hydrology has operated as before; however, our improved understanding and quantification of its processes have provided a better basis for deciding how to manage forests for water supply and control.

Three broad groups of interacting hydrologic processes are those that affect (a) rainfall, snowfall, fog drip, and condensation; (b) water storage and delivery; and (c) energy transfer, especially in evaporation. For each process, we present some measurement results and their variability and discuss how these affect the management of forests for water supply and control. We will describe how the hydrologic processes affect each other, and the limitations of our ability to measure the processes and integrate them into models of watershed performance.

Water Inputs

Precipitation Measurement

Water introduced into the hydrologic cycle may be as rain, atmospheric moisture, or snow. Measurements of this moisture are subject to sizable and unknown error — particularly for snowfall, misty rain, or fog. Even rainfall may be subject to large errors in measurement. Court (1960) wrote: "Two identical rain gages 10 feet apart on a windy ridgetop can differ consistently in catch by 50 percent of the smaller." Glander (1966) reported average errors of 18 percent and maximum errors of 40 percent in measurements of precipitation.

Variation of precipitation in time and space can mislead one in estimating the average precipitation for watersheds. These variations are associated with different synoptic events in complex ways. Hiser (cited by Singh 1968) lists six types of events that produce precipitation in Illinois: cold front, warm front, stationary front, squall line, warm air mass, and cold air mass. Singh (1968) pointed out that each type of storm can produce different streamflow responses from a basin.

Atmospheric moisture other than precipitation can be a direct input of water into forest hydrologic systems. Condensation on snow or vegetation surfaces can add significantly to water contributions. (Condensation on vegetation surfaces is discussed below under "Interception Processes.") In maritime climates the vapor gradient may be toward snow surfaces on most nights through the year and during much of the winter. In California, West (1959) measured as much as 0.07 inch per day of moisture condensing on snow.

Snowfall

Accurately measuring the distribution of rain is difficult, but measuring the distribution of snow and the processes that determine it are doubly so. We do not know how to measure this input: it does not remain stationary, and additions and subtractions occur in amounts that surprise us. Rarely does snow just fall. It swirls about until it finds a surface to rest upon — usually a tree or the snow-covered ground. Depending on its path, the individual snow crystal may take only a few seconds or as much as a few weeks to reach the ground; then it may take off again into the atmosphere or to a new ground location.

The term "falling snow" is almost a misnomer; Kuz'min (cited by Miller 1964) reported that the average angle of falling snowflakes is only 4 degrees from the horizontal. Wind almost always accompanies snowfall in western forests; for example, Court (1957) found that in the Sierra Nevada only 2 percent of the precipitation fell during calm periods. Wind affects measurement of interception of rain and snow by trees.

Interception Processes

Part of the rain that enters the tree canopy adheres to leaves and branches; the tree may absorb some of this. The remainder either falls directly to the ground or flows along and drips from the leaves and branches (called throughfall), or it flows down stems to the ground (called stemflow).

The water films and drops held on the foliage and other surfaces are subject to evaporation. The amount of water that evaporates is called "interception loss." Interception loss is actually a part of total evapotranspiration, but its distinct implications in forest management necessitate discussing it separately here.

When rain falls, it wets the forest soil, but not uniformly. For some tree forms, the amount of water that drips from the branch margin is one and one-half times the average amount that reaches the ground under the tree. More than the average amount also reaches the ground at the stem. Different species perform differently, and a single tree may perform differently in different storms. A windy storm may shake droplets from limbs and foliage and thus promote a more even distribution of rain reaching the soil under the tree (Grah and Wilson 1944). A misty rain may drop most of its water on the windward margins of each tree (Kittredge 1948).

What happens to the rain intercepted by the foliage and stems? A few years ago this question had a very simple answer — it just evaporated; nobody considered complicated energy and mass relations. Now, interpretations of interception losses vary as widely as the measured amounts. Miller (1967) stated that only trivial amounts of snow can be lost by interception because there is not enough energy for evaporation. Conversely, other workers have reported interceptions of as much as 5 to 6 inches per year; losses by interception have exceeded estimated potential evaporation by a factor of 4 or 5 (Rutter 1967, Leonard and Eschner 1968, Leyton and Rodda 1972, Helvey 1967). The interpretation of interception losses has changed over the years. Even the process of interception is being questioned. Is water absorbed into leaves? Is water transferred downward through leaves ultimately to dry soil? Does the energy required to evaporate intercepted water reduce the energy available for transpiration (Murphy and Knoerr 1975)? What is the surface detention of interception? Is it represented by the regression constant in Zinke's (1967) equation

$$\text{Interception} = \text{function (storm precipitation)}$$

In misty rains and clouds, is interception negative?

Unfortunately, evaporative loss is difficult to measure (Hoover 1971). It is conventionally approximated by exposing several rain gages under the forest canopy and one or more gages in a nearby opening in the forest. The average difference in catch between these exposures (usually corrected for stemflow) is an estimate of the interception loss.

Studies of interception by mature hardwoods (Helvey and Patric 1965) and by white, shortleaf, and loblolly pines (Lawson 1967, Helvey 1967), estimated from 1-day rainfall frequencies of storms greater than 0.10 inch, have shown an annual interception of 4.3 inches by hardwoods, or 8 percent of the annual precipitation; and 9.2 to 12.1 inches for pines, or 17 to 22 percent of the precipitation, in South Carolina's Piedmont (Swank 1968). When 6-month growing and dormant seasons have equal amounts of rainfall, about 60 percent of interception on hardwoods occurs during the growing season.

In most of western North America, even where snow is the dominant form of precipitation, interception losses from rainfall are significant in spring, summer, and fall and during an occasional rainstorm in winter. Western conifers intercept about the same amount of rainfall as some eastern pine stands. Interception by old-growth Douglas-fir in Oregon in summer averaged 24 percent; during the frequent rainy periods of winter months it was 14 percent (Rothacher 1963). Price (1958) obtained almost identical seasonal values (22 and 14 percent) in a dense mixed pine-fir stand in central Arizona. During two summers, mature lodgepole pine in Colorado intercepted 30 percent of the rainfall (Wilm and Niederhof 1941).

In the drier part of the West, more widely spaced conifers intercept less preciptation. Ponderosa pine in the southern Sierra Nevada of California intercepted 12 percent of annual rainfall (Rowe and Colman 1951). In central Arizona the discontinuous canopies of alligator and Utah junipers intercepted 10 and 17 percent, respectively, of the precipitation over a 1-year period (Skau 1964). Chaparral in the Sierra Nevada and in southern California intercepts from 5 to 12 percent of annual rainfall (Hamilton and Rowe 1949).

Snow Interception

The influence of wind on the differential deposition of snow in the forest and on the transport of snow from tree crowns is readily seen. Thus, values for interception that are derived by comparing the difference between snow accumulation within the forest and in the open are known to overestimate the evaporation loss of snow held on the canopy (Hoover and Leaf 1967).

Differences between maximum snow water accumulations in the open and those under hardwood and pine stands have been used as rough estimates of snow interception; these differences suggest that the forest intercepts about the same proportion of snowfall as of rain (Sartz and Trimble 1956, Hart 1963, Dunford and Hiederhof 1944, Rowe and Hendrix 1951). In New Hampshire, snow water contents of 5.5 and 5.7 inches, respectively, were measured in 40-year-old red pine and white pine stands; 7.0 inches in a hardwood stand; and 6.8 inches in the open, equivalent to an 18 percent interception by pine (Hart 1963). In the Adirondacks, maximum snow water contents were 9.0 inches under large hardwoods and 6.9 inches under red spruce and balsam fir, or 23 percent less in the conifers (Lull and Rushmore 1960). Bringfelt and Harsmar (1974) in Sweden reported an interception loss, in a pine stand having about 50 percent canopy cover, equivalent to 26 percent of the precipitation in the open.

Mature conifers in western snowpack zones intercepted 10 to 30 percent of the snowfall; some examples are:

	Interception	Reference
	Percent	
Rocky Mountain Area		
Lodgepole pine, Colorado	23	Dunford and Niederhot 1944
Ponderosa pine, Idaho	24 to 30	Connaughton 1935
Central Sierra Nevada, California		
Ponderosa pine	10	Anderson 1976
White fir	12	Kittredge 1953
Red fir	20	Kittredge 1953
Sugar-Ponderosa pine	28	Kittredge 1953

Interception and Floods

The forest's initial influence on a flood-producing rainstorm is the amount it intercepts and stores in the canopy. This interception is a major influence only in light showers; it is most effective for brief storms, but its effectiveness dwindles rapidly as storm size increases.

Few data on the interception of flood-producing rainstorms are available; very likely interception loss in such heavy storms would be little more than the 0.2 to 0.4 inch estimated for 2-inch storms (Helvey and Patric 1965, Helvey 1967, Lawson 1967, Rogerson and Byrnes 1968). For instance, in the Douglas-fir region on the Pacific Coast, interception averaged only 4 percent of the rainfall in storms 8 inches or more (Rothacher 1963).

Interception loss, of course, reduces the amount of flood-producing rainfall that reaches the stream; but, as Hoover (1962) noted, "when it is remembered that most land areas have some type of plant growth similar to tree foliage, which intercepts rain, it is doubtful whether canopy interception by forests is of significance in reducing flood peaks." So much for the interception of rain; condensation of vapor during rainfall may be much more important during rain-on-snow storms.

Variability of Interception

Interception is a subtraction by trees or other vegetation from total precipitation and thus reduces the amount of moisture that reaches the forest floor. In certain situations trees can also trap moisture from saturated airflow. This phenomenon, found worldwide, is variously called fog drip or negative interception; it may be called horizontal precipitation if it is liquid and rime, or hoarfrost if it is solid. In the upper-slope forests of eastern Washington, for instance, horizontally intercepted moisture, forming rime and hoarfrost on lodgepole pine, amounts to 0.05 to 0.06 inch per day, and accumulates 3 to 4 inches of water during a winter (Berndt and Fowler 1969). In northern New Mexico, the amount of rime falling from an aspen canopy to the snow surface ranged from 0.02 to 0.2 inch per storm. The annual amount of moisture addition at this high-elevation site was estimated to be 1.0 inch (Gary 1972). Kittredge (1948, p. 117-118) reported that May to October fog drip under a 40-foot big cone spruce and 80-foot ponderosa pine, at 5,850 feet elevation on Mt. Wilson in southern California, was approximately 25 and 38 inches, respectively — so that total catches under the trees were 2.11 to 2.65 times the catches of precipitation gages in the open.

Forested coastal areas particularly may trap substantial atmospheric moisture. In Japan, small trees were 6 to 10 times more effective than grass or bare ground in trapping sea mists (Hori 1953 and Reynolds 1967). The front surface of the forest was about three times as effective as the top surface. Also, a tall, open, broad-leaved forest, collecting as much as 0.03 inch per hour, was almost as efficient as spruce forest. On the Oregon coast during a period of 142 days, total precipitation was 45 percent greater under a stand of Sitka spruce and western hemlock than in the open: 36 inches under the trees and 25 inches in the open. Describing this study and others, Kittredge (1948) concluded that "In regions of frequent fogs of fine misty rains . . . fog drip may at certain seasons increase the precipitation reaching the ground by amounts up to two to three times the precipitation in the open." Further substantiation came when Ekern (1964) reported on a 3-year study of a cloud-swept ridge in Hawaii; cloud drip plus rain averaged 130 inches per year under Norfolk Island pine, whereas precipitation in the open averaged only 50 inches. It is interesting to note that 30 inches of the 80-inch increase occurred during rainless days. This water was largely saved for irrigation use, for little infiltrated into the iron-pan soil in this rather unusual case. Fog drip is largely a forest-margin phenomenon, but condensation of atmospheric moisture on vegetation may be more important than has been realized. Condensation on snow was discussed earlier.

In conclusion, there is no question of difference in precipitation catch between gages under forest canopy and those in protected openings. The soil beneath dense canopies generally receives less rainfall than the soil in openings, and more snow is caught in openings and their margins. This redistribution of incoming precipitation is an important influence of the forest (Anderson 1967b, Hoover 1973, Haupt 1973). In snow conditions, part of the evaporated water may be recondensed on the snow held on foliage, and thus increase the melt and drip to snow cover beneath; part may similarly be transferred from tree to atmosphere to snow cover. In neither case does intercepted water become wholly an evaporative loss. The amount of evaporative loss from precipitation held on the canopy is in question. With rain, even the water evaporated from foliage is not entirely lost because interception of moisture and subsequent evaporation are to some degree in lieu of transpiration. However, intercepted water may evaporate at rates much higher than transpiration rates. Nor is interception peculiar to trees. A wheat field or a 10-story building can intercept as much of the rainfall per unit area as a hardwood forest. Interception to some degree is a function of being. There would have to be exceptions; the hauli Koa of the dry side of Hawaii folds its leaves at the first drop of rain, presumably to avoid interception.

Surface Storage

The term "surface storage" includes temporary storage as surface detention—water enroute over the soil surface, water in the forest floor or litter, water ponded in depressions in the soil surface, and water held in the snowpack. Water stored in vegetation is also sometimes considered to be in surface storage.

Trees store little water internally. Mature beech and yellow birch on a good site may contain 7 to 15 thousand gallons per acre in their stems and branches at summer's end (Satterlund 1959), equivalent to a depth of about 1/4 to 1/2 inch of water; and old-growth redwood may contain as much as 150,000 gallons, an area-depth of about 5-1/2 inches.[2]

Snowpacks may contribute to surface storage both in the frozen phase and as free water. The volume and duration of detention depend on such conditions as depth of snow, air temperature, pore size, and initial free water content (Corps of Engineers 1956, Smith and Halverson 1969, and Smith 1974). Greatest detention is in the warm snowpacks of the Sierra Nevada and the Pacific slopes of the northern Rocky Mountains. Some water may be detained over winter, only to be released when the snow melts.

Snowmelt detention time is about 5 hours in the 4-square-mile Castle Creek Basin in the Sierra Nevada; measured daily runoff is equivalent to about 0.8 inch of water over the whole basin. Maximum free water in snowpacks may be as much as 18 percent of a 48-inch pack with 29 inches water equivalent; Anderson and others (1963a) reported that 5 inches of free water was detained in the pack. In a test of simulated rain on snow, 10.56 inches of water was applied to a 66-inch pack of 30 percent density; 8.9 inches of the applied water were held by the pack (Smith and Halverson 1969).

Forest cover delays snowmelt by shading and thus extends the time that the snow is held in surface storage. Conifers with persistent foliage naturally delay melt more than deciduous hardwoods. In the study of a 3-day rainfall-snowmelt flood in Oregon, Anderson (1969) estimated that forest shading reduced the melt rate by 40 percent (and flood flow by 10 percent). Studies of two California rain-on-snow floods gave similar results (Anderson 1970a).

Though snow under forest cover melts later and persists longer than snow in the open, it may melt more rapidly once it begins. This happens because melting occurs later in the season when temperatures may be much higher. A mixture of forest and open areas on a watershed may promote snowmelt at different times and thus reduce streamflow peaks. Topography also desynchronizes melting—snow on southerly aspects may disappear before much of the snow melts on northerly aspects.

Surface storage of water generally affects the rate of runoff more than the water yield. Surface detention is clearly a significant phenomenon in the hydrology of snow-zone forests. The paths and flow rates of much of this detained water are related to energy disposition within the forest environment, to soils and to local topography; the management of these forests may be effective or not, depending on how these paths, rates, and amounts of detention are modified.

Water stored on the surface of the soil eventually leaves the surface as overland flow, evaporates to the atmosphere, or infiltrates into the soil.

Almost all of the precipitation that reaches the ground sooner or later either infiltrates into the soil or leaves the surface as overland flow, often ambiguously termed surface runoff. The amount of overland flow is largely determined by the relation between infiltration capacity, storage opportunity, and rainfall intensity. Thus those forest practices and conditions that severely limit the infiltration capacity of the soil increase overland flow.

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[2] Zinke, Paul J., and Peter E. Black. 1964. Soil moisture observations around old-growth redwoods. (Paper presented before the Hydrology Section of the American Geophysical Union, Western Regional Meeting, Seattle, Washington, Dec. 1964.)

Infiltration Processes

Infiltration capacity is the rate at which water can enter the soil surface, and is usually specified for a particular condition of rainfall or snowmelt, soil frost, soil-water content, and wettability.

How is infiltration capacity measured? A wide variety of infiltrometers has been invented; they all use either artificial rainfall or surface flooding of relatively small areas. In general, their determinations serve only as indexes of broad differences of surface conditions which may or may not affect infiltration processes under natural rainfall in forests. Another technique involves analysis of hydrographs, in which rapid rises in the streamflow hydrograph are assumed to have resulted from rainfall rates that exceed infiltration capacity.

East or West, rainfall in the undisturbed forest rarely produces overland flow that results solely from limited infiltration capacity. Where storage capacity remains, the forest floor developed under uncut, unburned, and ungrazed forest readily absorbs and transmits downward the water from even extreme intensities of rainfall. Because of the persuasive logic of the infiltration concept of streamflow generation, which applies to many nonforest areas, even forest hydrologists were slow to recognize that overland flow is virtually absent from the mature undisturbed forest. Realization of this fact grew from reports by Hoover and Hursh (1944) for North Carolina forests, of Anderson (1962b) for California, Rothacher (1965a) for Oregon, Muller (1966) in the Allegheny Plateau of New York, Hewlett and Hibbert (1967) confirming the North Carolina observation, Yevjevich (1968) for Colorado, and Tsukamoto (1966a) for Japanese forests. From these general conclusions and many specific reports, the admonition of Hewlett and Hibbert (1967) seems appropriate: "In the case of forest land begin with the assumption that all flow is subsurface flow until there is evidence otherwise."

A test in southeastern Alaska provided the ultimate demonstration: Over a 30-day period more than 400 inches of water was sprinkled over a steep brush-covered slope without producing overland flow; about two-thirds reached the channel as subsurface flow; the remainder was lost to deep seepage or evapotranspiration (Patric and Swanston 1968).

Overland flow seldom occurs in the forest even during flood-producing rainfall. For instance, field examinations following the flood caused by Hurricane Diane in August 1955 revealed very little overland flow in the Poconos of Pennsylvania or in New England. Signs of such flow were found only on slopes greater than 50 percent at points where, presumably, subsurface flow intersected the surface.[3] Of course, local areas have overland flow, produced chiefly by roads, skid trails, rocky areas, and many small areas where infiltration is impaired.

Infiltration capacities of forest land not only exceed rainfall intensities; they may, for example, also absorb overland flow from adjacent natural rock outcrops, agricultural lands, and roads. In the driftless area of southern Wisconsin, most overland flow from open fields on ridges infiltrates into the forest slopes below and does not reach the valley. Over a 4-year period, 187 storm runoffs of 10 cubic feet or more were measured at gages above forest boundary; only 18 of these runoff volumes were recorded by gages in the valley below the forest. Overland flow from the upland fields infiltrated into the forest floor and seeped into valley bottoms (Curtis 1966). Packer's (1967a) study of the ability of the forest floor to absorb runoff from roads showed that the width of the protection strip required to keep runoff and sediment out of streamflow depends on several soil, cover, and topographic factors.

There are sure to be exceptions to any generalization in forest hydrology. Overland flow may occur in the forest under some special conditions. Recent research in Nevada, California, and Arizona has shown that sometimes there is a nonwettable soil layer 1/2 to 1 inch below the surface, formed by decomposition of organic matter (DeBano and others 1967, Cory and Morris 1968, Scholl 1975). Forest fire may cause the development or intensification of such a layer. Although the phenomenon has been observed during small-scale tests when water was artificially applied to undisturbed forest soils under red fir, its extent and importance in unburned soils have not been demonstrated because once wetted, these same soils showed

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[3] Varney, G. L. 1955. Some aspects of forest land behavior during the floods of August 1955. (Report on file, Northeast. For. Exp. Stn., Upper Darby, Pa.)

high infiltration rates. Nonwettability of burned areas is discussed later.

There are occasional reports of overland flow across a shingle-like cover of hardwood litter (Pierce 1967, Hoover 1962). This is a local phenomenon, and the flow infiltrates the soil within a short distance. Whipkey (1969) observed several such overland flows in a hardwood forest where simulated rainfall was applied at intensities of 5 to 30 inches per hour for periods of 60 to 150 minutes.

Evidence of apparent overland flow, such as small piles of leaves and twigs, and even exposure of the mineral soil, can often be noted in smaller draws or the drainageways between microridges. Closer observation usually shows that water infiltrated the upper slope and reappeared downslope or in the draw. This happens not because of limited infiltration capacity but because of limited capacity for storage and percolation and channel expansion; no amount of improvement in infiltration capacity at the point where the rain fell will mend it. Subsurface storage and detention become the dominant hydrologic processes.

Watershed Storage

The storage capabilities of a watershed largely determine what proportion of a flood-producing rainfall will reach any damage point downstream and at what rate. In its broadest sense, storage includes all aspects of retention and detention: interception; surface storage on the soil; storage in the vegetation, soil, and underlying rock; and storage in the channel. Interception and surface storage have already been discussed; detailed discussion of channel storage is beyond the scope of this report.

Soil-water storage accounts for the water from the time it infiltrates the soil until it leaves to go to groundwater, to streamflow or other surface water, or to the atmosphere by evaporation from the soil surface or transpiration from foliage.

Storage is of two types, detention and retention. These are relative terms, detention denoting that moisture in the soil is detained only temporarily as it makes its way towards groundwater or streamflow, retention being that water retained, against gravitational forces, and later discharged to the atmosphere. Substitution and exchange, which occur among all components of storage and delivery, impose problems of measurement.

Measurements of soil water range from laboratory analysis of soil samples,[4] through such physical indicators of field water content as resistance, capacitance, and "adsorption" of neutrons, to inference of soil water from hydrograph analysis. Tracing with chemicals and tritium has added some information about the paths and rates of flow within the soil.

Detention storage, drained by gravity, and retention storage, held against gravity, have often been equated to the amounts greater and less than field capacity, respectively. Field capacity has been defined as the amount of water held in a soil after excess gravitational water has drained away and after the downward movement has materially decreased (Veihmeyer and Hendrickson 1931). More than 25 years ago, Edlefson and Bodman (1941) reported that the simple drainage of soil/water to moisture contents less than normal field capacity was an important source of long-term discharge of water. More recently, Hewlett (1961) and others have demonstrated that slow drainage of soil moisture in the range of field capacity may be the source of a large proportion of the base flow of headwater streams.

Forest soils are generally less dense than similar soils not covered by forest and may have greater capacity for detention but less capacity for retention. Thus, for Coastal Plain soils of Mississippi the drainage capacity (total pore volume minus volume held at 1/3 atmosphere tension) for surface forest soils has been found to average 35 percent by volume, contrasted to 20 percent for old fields and pastures. Retention capacities (difference in volume between the amounts held at 1/3 and at 15 atmospheres of tension) averaged 14 percent for surface soils of the forest and 17 and 14 percent for old-field and pasture soils (Broadfoot and Burke 1958). In forest soils, the density, the retention capacity, and the total volume of stored water are highly affected by the amount of

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[4] In laboratory tests of soil, water held against gravitational forces (retention capacity) is taken as the amount held against a tension of 1/3 atmosphere. Water held too tightly for extraction by transpirational forces is taken as the amount held against a tension of 15 atmospheres. Maximum storage is taken as the water content when all pores are occupied. Detention storage capacity is taken as the water content when all pores are occupied. Detention storage capacity is taken as the difference between maximum storage and retention capacity.

Table 1—*Representative soil depths of forested watersheds*

Watershed location and reference	Soil depth		Subsoil weathering[1]
	Range	Average	
	Feet	*Feet*	
(1) Northern United States	2 to 8	4.7	–
(2) Mid-South United States	–	6	–
(3) N. Sierra Nevada, Calif.	15+	–	To 70 ft
(4) Northern Coast, Calif.	4 to 5	–	Yes
(5) Hubbard Brook, N.H.	–	5	–
(6) Fernow, W. Va.	3 to 5	–	–
(7) Coweeta, N.C.	3 to 6	–	–
(8) H. L. Andrews Exp. Forest, Oreg.	3 to 6	–	Yes
(9) San Dimas Exp. Forest, Calif.	–	<2.5	Yes
(10) Fraser, Colo.	1 to 2	–	To 14 ft
(11) Central Sierra Nevada, Calif.	1 to 9+	3.5	–

[1] Dash indicates no data available; "yes" indicates weathering occurs but depth is variable.

(1) U.S. Dep. Agric. 1952
(2) Zahner 1956
(3) Ziemer 1968
(4) Gardner 1958
(5) U.S. Dep. Agric. Forest Serv. 1964b
(6) Reinhart and others 1963
(7) U.S. Dep. Agric. Forest Serv. 1957
(8) Rothacher and others 1967
(9) Rowe 1963
(10) Love and Goodell 1960
(11) Anderson and Richards 1961

organic matter in the soil. Additions of from 1.2 to 10 percent of organic matter have increased the amount of water retained in clay soils by 34 percent, in fine sand by 150 percent, and coarse sand by 780 percent (Feustel and Byers 1936). Coile (1938) found similar increases. Organic matter decreases soil density, and therefore has a direct effect on soil depth.

Depth of forest soils throughout the country varies widely but generally ranges between 2 and 8 feet. Some reported soil depths to parent material, or to impermeable layers, are summarized in *table 1.* The mid-South and the Pacific Northwest have deeper forest soils. For the upland pine forests of the mid-South, Zahner (1956) considered the upper 6 feet of surface soil to be the effective root zone. In deep soils and under intense climatic stress rooting is deeper. At 2900 feet elevation in the Sierra Nevada, Ziemer (1968) found summer depletion under pine to depths greater than 15 feet. In the redwood—Douglas-fir region of northern California, soils as deep as 4 to 5 feet rest on weathered, shattered, water-holding parent materials (Gardner 1958) which may furnish water to the trees during periods of soil moisture stress.

The maximum opportunity for soil-water storage that the forest can generate at any one point is essentially the difference between field maximum and field minimum moisture contents throughout the rooting depth. Several of these maximums, derived from soil-water studies, are given in *table 2.* They range from 2 to 23 inches and, according to soil texture, from 1 to nearly 4 inches per foot of depth. The maximum soil-water depletion measured (Ziemer 1968) was 22.6 inches for an isolated pine in the Sierra Nevada.

Retention storage capacity varies greatly, especially with soil depth and texture. Although many forest soils are often classified as shallow (from 5 or 10 to 20 or 30 inches deep), they can retain several inches of water after prolonged drying. However, when flood rainfall occurs, the first extraction from rainfall at any one point depends not so much upon the capacity as upon the amount of drying since the last significant rainfall, i.e., the retention opportunity.

A watershed's maximum opportunity for soil-water retention can be estimated from the difference between storm rainfall following a prolonged drying period, and storm discharge. Estimates differ widely between Eastern and Western watersheds. Some characteristic values are:

	Maximum storage opportunity	*Condition*	*Reference*
Location:	*Inches*		
Northeast	4.0-4.5	During major storms	Hoyt and Langbein (1955)
East	1.5-2.5	During major storms	Hoyt (1942)
	4.0-5.5	After long drying	Reinhart (1964a)
N. Sierra Nevada	20	After summer drying	Anderson (1963)
	8	After mid-winter drying	Anderson (1963)
San Gabriel Mts., Calif.	22	After long drying	Rowe[5]

Opportunity for retention storage varies seasonally in the East. When the soil has been recharged by autumn rainfall after the growing season, retention opportunity is at a minimum until spring. Frequent rainfall during the growing season in the East can severely limit the retention opportunity for flood rainfall. For example, estimates of maximum retention opportunities on the Fernow Experimental Forest in West Virginia were based on daily water-budget estimates over 11 growing seasons (April-November).[6] Even in the dryest season (1957), for the 10-inch retention capacity, opportunity was more than 2 inches on only 61 days of the 244-day season; the mean for the season was 1.3 inches. The mean retention opportunity in 1956 (a wetter season) was only 0.25 inches.

Table 2–*Maximum soil-water storage under selected forest stands*

Location and forest cover	Sampling depth	Soil-water storage
	Feet	*Inches*
(1) New Jersey Coastal Plain		
Shortleaf pine	10	8
(2) Southeastern Ohio		
Oak	3.3	7 to 9
(3) Western North Carolina		
Appalachian hardwoods	7	11
(4) Piedmont of South Carolina		
Loblolly pine	5.5	5
Loblolly pine-hardwood	5.5	9
(5) Missouri		
Oak-hickory	3.3	9
(6) Southern Arkansas		
Southern red and post oaks, sweetgum; loblolly and shortleaf pines	4	12
(7) Texas		
Post and blackjack oaks	2	5
(8) Cascades, Oregon		
Douglas-fir, western hemlock	2 to 6	2 to 23
(9) Central Sierra Nevada, Calif.		
Red fir (subalpine)	4 to 10	8 to 16
(10) Southern Sierra Nevada, Calif.		
Woodland chaparral	3	7
Ponderosa pine	6	11
(11) San Dimas, Calif.		
Mixed chaparral	5	11

Compiled as follows:
(1) Lull and Axley 1958
(2) Gasier 1952
(3) Helvey and Hewlett 1959
(4) Metz and Douglass 1959
(5) Lull and Fletcher 1962
(6) Moyle and Zahner 1954
(7) Koshi 1959
(8) Rothacher and others 1967
(9) Knoerr 1960
(10) Rowe and Goldman 1951
(11) Rowe and Colman 1951

Farther south on deeper soils, opportunities for storage are much greater. In the Piedmont of South Carolina, for instance, daily soil-water measurements for 3 years under a 50-year-old shortleaf pine—hardwood stand (Metz and Douglass 1959) recorded median storage opportunity for two soil-water seasons: January to April, about 2 inches and May to December, about 6 inches.

In major river basins on the west side of the Sierra, the soil-water deficit in the fall has been estimated to range from 4 to 10 inches. Rock storage varies from negligible amounts in granite batholith to 45 inches or more in highly fractured igneous rock and unconsolidated alluviums (Anderson 1962b). The retention for whole large

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[5] Rowe, Percy B. 1955. Rainfall disposition by hydrologic years 1938-39 through 1952-53, Volfe Canyon, Watershed IX, San Dimas Experimental Forest. (Unpublished report on file, Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.)

[6] Unpublished report, Northeast. Forest Exp. Stn., Parsons, West Virginia.

watersheds has exceeded 20 inches in early winter storms and 8 inches in succeeding midwinter flood-producing storms (Anderson 1963). When compared with the yearly evapotranspiration loss (Rothacher and others 1967), data from Dyrness (1969) on the maximum storage opportunity at the end of summer in the H.J. Andrews Experimental Forest indicate that the opportunity must be restored several times during the year to account for a loss of as much as 33 inches.

These measurements of retention storage opportunity and recovery of retention capacity, in one case in the middle of winter and in the other case repeatedly throughout the year, cast some doubt on the validity of the simple concept of maximum retention storage in these watersheds. This concept is the familiar single linear reservoir with a single spillway whose discharge is proportional to the storage; however, Sugawara (1967) showed that multiple reservoirs in series and parallel, with complex outlets to each other, are necessary to simulate streamflow hydrographs; equally complex analogues may be needed to explain adequately the performance of forests in flood prevention and streamflow yield generally. Thus, maximum retention storage may never be achieved in some of these watersheds, for some areas may always have retention capacity that does not become full because of the lack of input water or because of input channels which require heads of longer duration. On some watersheds, near-maximum retention opportunity may be achieved only after a long drought; on others, only when water is available for percolation throughout the year will some of this excess retention storage be filled. The nature of these multiple reservoirs and their different input and output channels controls storage and its product, subsurface flow.

Subsurface Flow

Subsurface movement of detained water on forested slopes has been widely studied in recent years, yet we still know little about its rates of movement. Water entering the surface soil sometimes flows downward until it reaches a layer of different texture. Then it flows downhill along this interface until it finds opportunity for further penetration. Such lateral flow has been measured and described by Whipkey (1969), McDonald (1967), Minshall and Jamison (1965), and Smith (1972). At other times the flow is simple drainage from the lower slope reaches, such as Hewlett and Hibbert (1967) reported, rather than flow occurring at the top of the B horizon or at a layer of finer soil texture. Ragan's analysis (1968) showed that only a small area of the forested watershed he studied contributed flow to the storm hydrograph. The contributing area, a function of storm duration and intensity, was not uniformly distributed along the channel, but was localized in only a few zones. This subsurface drainage, together with rainfall on saturated soils and on water surfaces, accounted for the occasional very high floodflows discharged from upland forest watersheds in the absence of widespread appreciable overland flow. Martinec (1975), from a study of the tritium content of subsurface flow, concluded that this flow included some water that had been in subsurface storage for several years.

Despite the considerable progress in both the conceptual and the experimental studies of subsurface flow, the rates of flow and the spatial distribution of the flow paths are basically unmeasureable. Techniques measuring these flows must be developed because knowledge of these rates and distributions are crucial to understanding and predicting water use by vegetation, zones of saturation and soil instability, and the potential of parts of any watershed to generate flood peak flows.

Peak Flows

Subsurface flow in the forest can produce substantial peak flows in streams. Thus, completely or partly forested watersheds have produced floods periodically *(table 3).* Hursh (1943) reported a peak of 167 csm (ft^3/s/mi^2) from a small, forested, high-elevation watershed in western North Carolina during a low-intensity storm in which infiltration was not limiting. In New Hampshire, in October 1959, peak discharges from two well-forested watersheds of 105 and 39 acres were 451 and 462 csm respectively, during a 7-inch storm; maximum measured 1-hour rainfall was just over 1 inch.[7] Storm flows, calculated by the procedure of Hewlett and Hibbert (1967), were 76 percent of rainfall for the larger watershed and 85 percent for the smaller. From much larger watersheds (45 to 143 square miles) peak flows of 126 to

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[7] Storm peaks and storm damage of October 23-25, 1959, Hubbard Brook Experimental Forest and White Mountain National Forest, New Hampshire. (Report on file at Northeast. For. Exp. Stn., Durham, N.H.)

Table 3—*Record peak flows and percentage of forest cover for watersheds approximating 25, 100, 500, and 1000 square miles*

Stream	Station	Drainage area	Peak flow	Forest cover
		Mi²	*Ft³/s/mi²*	*Percent*
North Atlantic Slope Drainage				
Ellis River	Jackson, N.H.	28	529	100
Rondout Creek	Lackawack, N.Y.	100	267	80
Rapidan River	Culpepper, Va.	465	125	53
N. Branch Potomac River	Cumberland, Md.	875	102	82
South Atlantic and Western Gulf of Mexico Drainage				
Morgan Creek	Chapel Hill, N.C.	27	1110	61
Henry Fork	Henry River, N.C.	80	391	88
Yadkin River	Wilkesboro, N.C.	493	324	90
Rocky River	Norwood, N.C.	1370	113	55
Ohio River Basin				
Elk Creek	Elk Park, N.C.	42	655	67
Watauga River	Sugar Grove, N.C.	91	560	62
Watauga River	Butler, Tenn.	427	168	64
Cheat River	Rowlesburg, W. Va.	972	129	87
Pacific Slope Basins in California				
San Antonio Creek	Claremont, Calif.	17	1267	63
W. Fork San Gabriel River	Camp Ricon, Calif.	102	334	100
Los Angeles River	Los Angeles, Calif.	512	131	28
N. Fork American River	Rattlesnake Branch, Calif.	999	95	90
Pacific Slope Basins in Washington and Upper Columbia Basin				
N. Fork Skokomish River	Hoodsport, Wash.	60	388	75
Wynooche River	Montesano, Wash.	105	238	90
Skykomish River	Gold Bar, Wash.	535	148	78
Sauk River	Sauk, Wash.	714	96	77

Source: Linsley and others 1949

more than 300 csm were registered. Corbett and others (1975) studied flow from a 20-acre watershed in Pennsylvania where artificial rainfall was applied to three areas: ridge, midslope, and near-channel. Quickflow dominated the flow regime, being 65 to 85 percent of the total flow, irrespective of the part of the watershed to which the simulated rainfall was applied.

Subsurface flow from low-intensity, long-duration rainstorms in Oregon may have maximum rates of runoff that are as much as 80 percent of the average rate of measured rainfall for the preceding 12 to 24 hours. For shorter durations, the maximum rainstorm of record (12.5 inches in 3 days, 1.9 inches in 6 hours) on a 237-acre watershed of Douglas-fir and western hemlock produced a peak of 139 ft³/s/mi² (Rothacher and others 1967). This peak runoff is the equivalent of only 0.22 inch per hour, about two-thirds of the *average* rainfall rate of 0.32 inch per hour in the 6-hour period. The modifying influence of the forested watershed on flood peaks from small experimental watersheds was strikingly illustrated in the storm that produced the Rapid City flood on June 9, 1972. Although prior rainfall was "apparently enough to fill available soil storage capacity and cause flow to respond almost immediately" to the additional high-intensity rain of 2.12

to 3.25 inches in 1 hour (Orr 1973), the records show that maximum hourly flow never exceeded about 15 percent of the maximum hourly rain. Tsukamoto's study (1975) of the role of forest floor litter in reducing peak flows showed that removal of litter increased peak flows from storms of less than 4 inches by 168 percent.

However, a high-elevation, steep, completely forested watershed without appreciable overland flow may produce greater volumes of stormflow per unit rainfall than many pastures and cultivated areas at lower elevations (Hewlett and Hibbert 1967). In the Northeast, generally, the greater the proportion of watershed that is forested, the greater the streamflow (Lull and Sopper 1967). These high flows, and the others tabulated above, do not show a negative "forest influence" but rather the integrated influence of the forest-occupied environment — with steeper topography, shallower soils, and more rain.

Erosion and sedimentation are discussed in detail elsewhere in this report. We must recognize here, however, that transported sediment stemming from erosion bulks flood flows and may increase flood stages. Even more important is the fact that deposits of sediment in stream channels reduce the carrying capacity and increase the frequency and severity of overbank flooding. Dirty flood water is more damaging than relatively clean water, and sediment left by a flood can cause a substantial part of its total damage. It follows, then, that as forest cover inhibits erosion, it significantly contributes to preventing flood damage.

Evapotranspiration creates storage opportunity in the soil so may affect floods and soil and slope stability, but also withdraws potential water supply.

Evapotranspiration

Evapotranspiration from the forest is powered by solar energy. It includes the evaporation of rain and snow intercepted by the canopy, the vaporizing of water that reaches the leaf surface in the transpiration, and the evaporation of moisture from bare areas, the wetted forest floor, or snow cover.

Transpiration

Transpiration accounts for most of the vaporization from the forest—perhaps 80 percent in hardwoods and 60 percent in conifers. The remainder is evaporation from rainfall and snowfall intercepted in the canopy, from snow and wet litter on the forest floor, and from the soil beneath. Transpiration is difficult to measure and is most often estimated indirectly from the difference between precipitation and streamflow during selected time periods, or estimated from a water budget developed from periodic measurements of soil water and precipitation, or estimated from aerodynamic or energy budgets.

Radiant energy is primarily responsible for evapotranspiration. The energy used is drawn from net radiation, which is the difference between incoming and outgoing solar and thermal radiations. Net radiation energy is used to heat air, soil, water, and vegetation; it is also used in photosynthesis, respiration, and evapotranspiration. By far the greatest portion of the energy is used in evapotranspiration and in heating the air. Evapotranspiration from thoroughly wetted forest soil is limited by the energy supply; during soil drought and high climatic stress evapotranspiration is primarily limited by the water supply, but the trees exercise some physiological control (Lee 1967).

Powered by radiant energy and dependent on available moisture, forest evapotranspiration tends to be greatest in warm and wet climates and least in cold, dry ones. This is indicated in the several comparisons of potential evapotranspiration (Thornthwaite and Mather 1957) for points centrally located in major forest types *(table 4* and *fig. 3)*.[8] The longleaf-slash location, the warmest, has the greatest potential; the lodgepole pine location, the coldest, has the least potential; and the more humid the climate, the more likely it is that actual evapotranspiration will approach the potential. Similar average potentials are a feature of such diversely located types as spruce-fir in Maine (21 inches) and ponderosa pine in Arizona (23 inches), of maple-birch-beech in New York (26 inches) and redwood in California (25 inches).

Slope and aspect combinations markedly affect the amount of solar radiation received on any given area and thus markedly affect evapotranspiration. In studying these relationships, Lee (1964), describing watersheds in terms of their average exposure and potential insolation, found strong negative correlation between the radiation indexes and annual streamflow from adjacent basins. He

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[8] Potential evapotranspiration is an estimate of maximum possible evapotranspiration, the evapotranspiration that would occur if water were fully available.

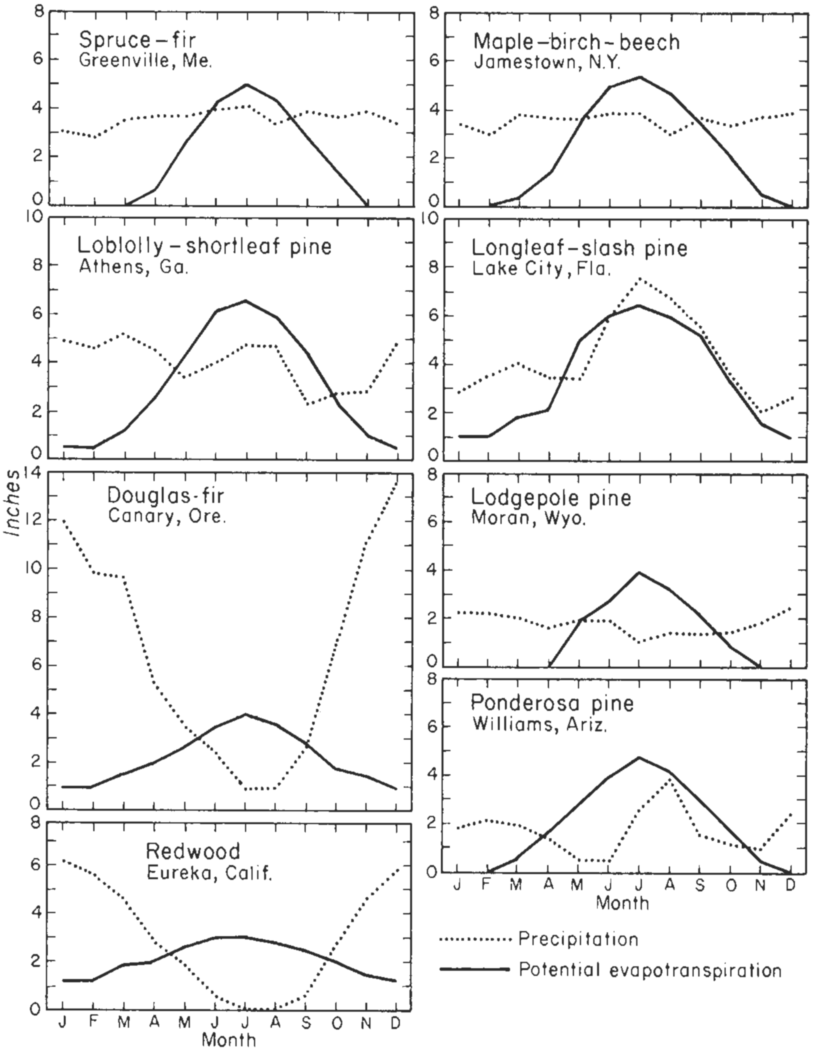

Figure 3—Mean annual potential evapotranspiration and precipitation at points centrally located in some major forest types.

Table 4—*Mean annual potential evapotranspiration, precipitation, and air temperature at points centrally located in selected major forest types*

Forest type	Location	Potential evapo-transpiration	Precipitation	Air temperature
		Inches	*Inches*	*°F*
Longleaf-slash pine	Lake City, Fla.	42	51	69
Loblolly-shortleaf pine	Athens, Ga.	36	48	63
Maple-birch-beech	Jamestown, N.Y.	26	43	49
Douglas-fir	Canary, Oreg.	26	79	52
Redwood	Eureka, Calif.	25	36	52
Red fir	Teakettle, Calif.	25	44	43
Ponderosa pine	Williams, Ariz.	23	21	49
Spruce-fir	Greenville, Maine	21	43	40
Lodgepole pine	Moran, Wyo.	15	21	34

assumed these differences to be attributable to differences in evapotranspiration. Because of differences in the energy they receive, slopes and aspects differ markedly in potential evapotranspiration. In southern Missouri, for instance, where the soil-water storage capacity is 10 inches, the calculated moisture deficit on a horizontal surface for a normal year was 3.9 inches; a 40° north slope had a deficit of 1.9 inches, and a 40° southwest slope had a deficit of 5.9 inches (Nash 1963). These studies did not consider the influence of advected energy. In attempting to use space- and time-integrated air temperatures, Chang and Lee (1969) used chemical sensors to integrate temperature with soil information and seasonal responses of plants. They believed that using this technique enabled them to prepare better estimates of water balance.

The amount of water evapotranspired from mature forests also depends on the amount of moisture available in the soil, which in turn is largely a function of soil texture and depth, and, of course, climate. With some exceptions (Anderson and Gleason 1960, Ziemer 1968, Rothacher and others 1967) the upland forest, regardless of type, receives sufficient radiant energy during the growing season to deplete most if not all of the available moisture. For example, in Arkansas (Moyle and Zahner 1954), South Carolina (Metz and Douglass 1959), Michigan (Urie 1959), and Colorado (Brown and Thompson 1965), the amounts of soil water withdrawn under conifers and hardwoods during the growing season were very similar, almost equally depleting moisture. Annual evaporative losses from white pine stands at Coweeta were greater than from hardwoods (Helvey 1967). This was ascribed to greater interception by the persistent foliage of the pine and not solely to greater depletion of soil water. The differences in the many phenological characteristics of individual tree species as they influence water use are as yet little known.

To some degree the trees themselves control transpiration—by controlling water loss through the stomates, which cover from 1 to 3 percent of the leaf surface. With an average density of 100 to 300 stomates per square millimeter, this loss can approach the rates of evaporation from free water (Slavik 1965). Opening and closing of stomates are controlled primarily by the water content of the leaf, but increases in light and rising temperatures also stimulate opening. The rates of water loss at specific stomatal openings are not constant but depend on atmospheric conditions. Lee (1967) suggested that careful study of the microstructure of leaf types and of their abilities to control transpiration seasonally would provide a rational basis for managing vegetation to increase water yield. Other investigators are far less optimistic (Idso 1968, Van Bavel 1968).

One influence on the stomatal mechanism is the available energy, which is determined in part by such forest characteristics as color, size, phenology, and vigor. The darker the forest, the lower its albedo; i.e., less of the incoming solar radiation is reflected. For example, summer albedos for birch-maple and white pine stands in New Hampshire were 0.17 and 0.14, respectively (Federer 1968); the pine had 3.6 percent more energy available for evapotranspiration. According to one estimate, darkening of the foliage by wetting can reduce albedo by 40 percent (Goodell 1967, citing Scholte Ubing). Stands having taller trees usually capture more radiant energy and have a lower albedo. Phenological differences are another factor: in Michigan, for instance, red pine stands rapidly deplete moisture in April and May, whereas hardwood stands do not begin until June, when their leaves are fully developed (Urie 1959). Finally, there is some evidence that the stage of growth influences water use. Black (1967) found that second-growth redwood stands depleted soil moisture more rapidly than old-growth stands, and Knoerr earlier (1960) reported that young red fir depleted soil moisture more than older stands. Kittredge (1948) showed that trees reach the culmination of their growth rate and their maximum leaf surface in fully stocked stands at between 15 and 60 years, and that transpiration is related to area of foliage.

Though we are accustomed to thinking that growing and dormant seasons control transpiration, even in some temperature climates—e.g., along the Pacific Coast—a true dormant season may not exist. Even when snow is on the ground, daytime air temperatures may reach 55 °F; tests of water transport through the trunks of pines, using heat pulse velocity and radioactive tracers, have indicated that sizable quantities of water are transpired during winter, spring, and early summer (Swanson 1967, Smith 1972). Such use may help explain why evapotranspiration in Douglas-fir forests (Rothacher and others 1967) is three to four times the maximum depletion of retention storage reported by Dyrness (1969), and may explain how 8 inches of soil moisture deficit could have been created in winter in the Sierra Nevada (Anderson 1963).

Evaporation

Evaporation from the forest floor or from snow surfaces can add significantly to transpiration as an evaporative loss at some places. Evaporative losses from the forest floor vary greatly. Aldon (1968) reported losses amounting to as much as 1.09 inches of moisture during a 30-day period of summer thunderstorms. Similarly, Rowe (1955) reported that about 0.1 inch of water was stored per inch depth of forest litter. In a 4-year period when annual precipitation averaged 49 inches, the water evaporated from the forest floor ranged from 3.0 to 5.2 percent of the precipitation for floor depths of 1 inch to 3.6 inches. Litter on the forest floor may range from negligible amounts to more than 20 tons of oven-dry material per acre (Kittredge 1948). The loss from 1 inch of litter was about 15 times the storage capacity; from 3.6 inches it was about 7 times the storage capacity. Total replenishable storage deficit was greater for bare soil than for soil covered by 1-1/4 inches of pine litter; the bare soil lost 10.7 inches of water per year by evaporation; soils covered by 1/2 inch or more of litter lost about 7 inches (Rowe 1955). In the Appalachians, evaporation of moisture from litter of hardwoods and white pine is only about 2 inches (Helvey and Patric 1965, Helvey 1967).

Evaporation of snow under the canopy can be slow: in a 3-year study, annual evaporation from January to as late as June under a dense lodgepole pine-red fir stand in the central Sierra Nevada amounted to only 0.4 to 1 inch of water (West 1962). In the southern Sierra Nevada, the 3-year average annual evaporation from snow was zero within the red fir forest, 0.5 inch in small forest openings, and 1.8 inches in large open areas (Anderson and Richards 1961). Intercepted snow in trees may evaporate as much as three times faster than snow on the ground because of the much lower albedo of the snow-foliage moisture (Leonard and Eschner 1968).

Water Yield

The water yield of an area is that part of precipitation that is not used on the watershed. Water used by the forest is derived from the combination of dormant season precipitation, soil water stored during the dormant season, plus summer rainfall. The minimum annual requirement of moisture for forest growth is about 20 inches of precipitation; from this the forest transpires about 15 inches. In the precipitation-evapotranspiration-water yield relationship, evapotranspiration is the most nearly constant element; each year it subtracts what the forest "needs" from total precipitation, which is variable. The residue, water yield, is the most variable element in the cycle; it includes both streamflow and groundwater recharge.

Groundwater

Water that seeps through the soil mantle and adjacent rock strata may move directly to a stream or into a groundwater aquifer. Most of the water that goes into aquifer storage eventually turns up as streamflow (though perhaps below the point where a particular watershed is gaged) or is utilized from wells.

Most research on small watersheds has necessarily been conducted in areas where the true groundwater component is relatively small. However, several European studies show the effects of forests on groundwater. In one study, clearcutting a stand that had 100 m^3/ha of pine caused the water level to rise as much as 40 cm (16 inches) (Heikurainen 1967). Thinning also raises the water level; the amount of rise depended upon the intensity of thinning. Mustonen and Seuna (1971) reported increased streamflow of 0.9 inch per year from peatlands after clearcutting of trees.

Streamflow

Average annual streamflow from major forest regions varies throughout the country from 5 to 50 inches, and monthly amounts vary from near zero to 25 percent of the annual total. Records of annual and monthly streamflows from eight forested experimental watersheds show some important characteristics (*table 5* and *fig. 4*). Differences in streamflow result mostly from the climatic differences among major forest regions. Maximum annual precipitation of 94 inches is about 4 times the minimum value, which is 22 inches; streamflow, as would be expected, varies more—from 61 to 2 inches; so the ratio of the maximum to the minimum is more than 30.

Table 5–*Mean annual precipitation and streamflow for selected forested watersheds*

Location	Forest cover	Area	Mid-area elevation	Precipitation	Streamflow	Precipitation less streamflow
		Acres	*Feet*	*Inches*	*Inches*	*Inches*
Hubbard Brook Exp. Forest West Thornton, N.H. (Watershed 3)	Northern hardwoods	105	2,050	48	27	21
Fernow Exp. Forest Parsons, W. Va. (Watershed 4)	Central Appalachian hardwoods	96	2,500	58	24	34
Coweeta Hydrologic Lab. Franklin, N.C. (Watershed 18)	Southern Appalchian hardwoods	31	2,700	72	36	36
Marcell Exp. Forest Grand Rapids, Minn. (Watershed S-2)	Bog black spruce	24	1,385	31	7	24
Fraser Exp. Forest Fraser, Colo. (Fool Creek)	Lodgepole pine, spruce-fir	714	10,400	22	12	10
Sierra Ancha Exp. Forest Ariz. (Middle Fork)	Ponderosa pine–white fir	521	7,150	32	3	29
Three Bar Exp. Watersheds Ariz. (Watershed D)	Chaparral	80	4,250	27	2	25
H. L. Andrews Exp. Forest Blue River, Oreg. (Watershed 2)	Douglas-fir	149	2,500	94	61	33

Fifty to 65 percent of precipitation appears as streamflow in northern hardwoods, Appalachian hardwoods, lodgepole pine-spruce-fir, and Douglas-fir; slightly more than 20 percent in bog black spruce in Minnesota, and less than 10 percent in ponderosa pine-white fir and chaparral in Arizona (*table 5*).

Monthly precipitation and corresponding montly streamflow differ widely among regions (*fig. 4*). The West and Southwest show the greatest seasonal variations. Streamflow from rainfall and snowmelt exceeds monthly precipitation in northern hardwoods during April, and in lodgepole pine-spruce-fir during June. Uniform winter streamflow in the lodgepole pine-spruce-fir, bog black spruce, and ponderosa pine-white fir types attests to cold winters with little snowmelt; in the chaparral, low streamflow is due to low monthly precipitation. The Appalachian hardwoods produce high winter and spring flows, mostly from rainfall, followed by greatly reduced summer flow despite no decrease in rainfall. The Douglas-fir region is notable for high winter and spring precipitation and streamflow, and low summer rainfall and streamflow. Even within regions streamflow varies with topography and geologic conditions.

Streamflow also varies from year to year. Variations in the annual discharge by major forest regions are least in the Northeast and on the Pacific Coast; somewhat greater in the South, Midwest, and Rocky Mountains; and greatest in the Southwest (Busby 1963). In the southern Sierra Nevada in California, year-to-year variation in streamflow was least from high-elevation forest and alpine areas; streamflow from mid-elevation mixed-conifer forest was next in variation, and low elevation woodland and brush produced the most variable flow (Anderson 1963). Throughout northern California, the years of extreme low flow, the 10-year minimum flow, occurred progressively from high elevation to low, from

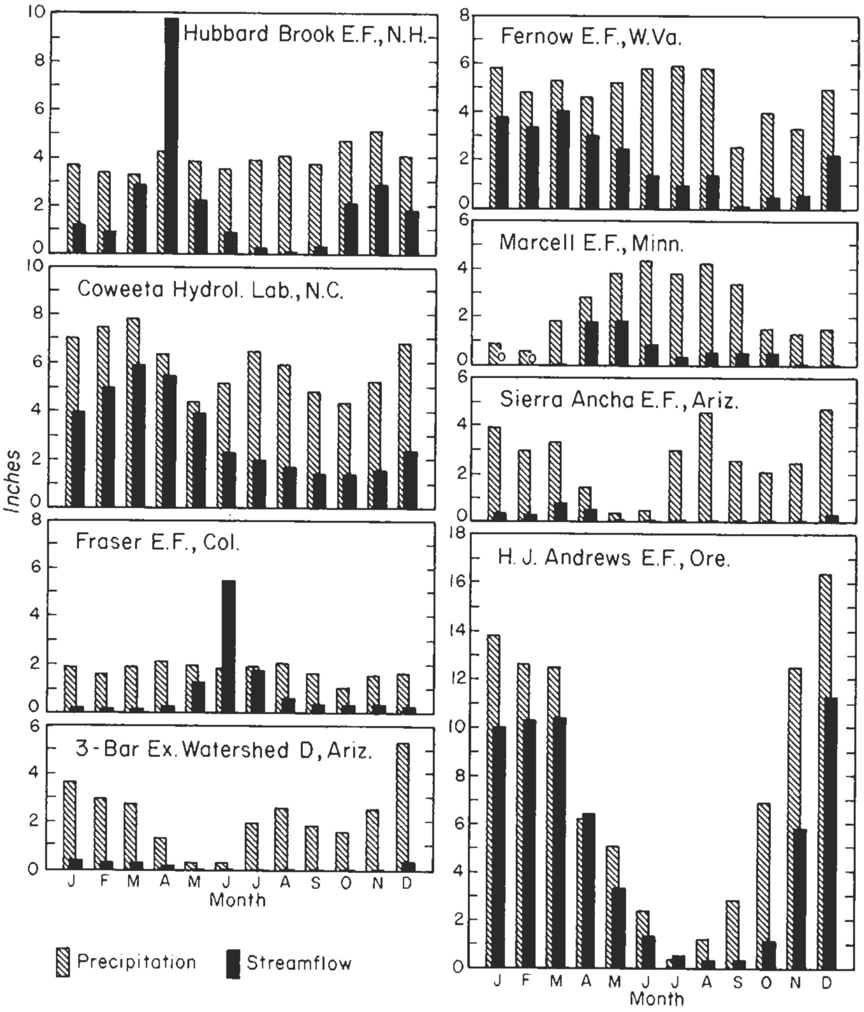

Figure 4—Mean annual precipitation and streamflow for selected experimental forests (E.F.) and other watersheds. Forest types are: Appalachian hardwoods at Fernow and Coweeta, northern hardwoods at Hubbard, bog-black spruce at Marcell, lodgepole pine and spruce-fir at Fraser, ponderosa pine and white fir at Siera Ancha, chaparral at 3-Bar, and Douglas-fir at Andrews.

northern latitudes to southern, from steep watersheds to less steep, and from watersheds with serpentine to watersheds with granite (Anderson 1975d).

Streamflow reflects local differences in physiography and climate. For example, in 137 watersheds in the Northeast, the average annual water yield among seven physiographic units ranged from 19 to 24 inches. Both annual and seasonal differences among regions were statistically significant at the 1-percent level, as were differences between clusters of watersheds within units (Lull and Sopper 1967). Yields can vary greatly within short distances. The same study recorded significant differences in annual and seasonal discharge within clusters of watersheds within a 30-mile radius. At the 4,700-acre Coweeta Hydrologic Laboratory in western North Carolina, average annual streamflow of small watersheds varies from 24 to 52 inches over an elevation difference of only 900 feet and a difference in average annual rainfall of 14 inches.

Within major forest regions some evidence shows that streamflow differs by forest type, particularly between hardwoods and conifers. In Michigan, water yield (as determined by groundwater measurements) from a 28-year-old jack pine plantation was 12.4 inches compared to 15.3 inches from 40-to 60-year-old deciduous stands nearby (Urie 1966). At Coweeta, streamflow from a mature white pine plantation, considering the difference in interception between pine and hardwoods, might be as much as 12 inches less than flow from the same site during an earlier period when it was covered by a hardwood stand (Swank 1968). After fifteen years, annual streamflow was 7.9 inches less in the pine-covered watershed; the decrease occurred in each month but was greatest in the dormant and early growing seasons (Swank and Douglass 1974).

Among partly forested watersheds in the Northeast, those having a higher proportion of forest have more streamflow. This has been attributed not directly to the influence of the forest but to associated climatic, topographic, and edaphic conditions that usually increase flow (Lull and Sopper 1967).

Modifiers of the Forest Influence

The effects of hydrologic processes on streamflow are determined partly by scale—storm size, watershed size, and topographic differences; but the effect of these three factors on the forest influence is usually less important than physiographic controls.

Storm Size

The effect of the forest on streamflow is frequently stated as a percentage rather than an absolute amount. It should be apparent at this point that some forest influences are relatively more important for stormflow resulting from small storms: interception accounts for a larger proportion of small rainfalls, and soil-water storage opportunity of any given magnitude subtracts a greater proportion from the smaller rainfalls. Some forest processes thus have less effect, proportionately, on extreme events.

The situation may be different when rainfall augments snowmelt; then the forest's effect on large flows may be equal to or greater than that on smaller ones, especially on large and diverse watersheds.

One may well argue that the forest retains or detains some portion of any rainstorm, including the general and protracted storms described above, and thus somewhat reduces flood discharge and its peak. In a general sense this argument has merit: the forest does this. To some degree and in some places improved forest conditions do it better, provided that management accomplishes the needed forest improvement or that it reduces creation of additional poor forest conditions to the minimum.

Watershed Size

Many hydrologists reason that forests have greater influence on flood peaks from small watersheds than from large ones. Hoyt and Langbein (1955) explained it this way: "The larger the drainage area, the longer it takes flood waters to assemble in the lower reaches of the main stem. For this reason detention of infiltrated water for any given length of time has a lesser effect upon flood runoff as the size of the basin increases."

The situation is not always that simple. The effect forests have on flood peaks depends on the location of the forests and on the dominant processes of flood generation upon which they operate. The opportunity to prevent flood waters from collecting in the lower reaches by establishing or manipulating forest has been little appreciated, for American forests generally occupy the headwaters of rivers, a position favorable for delaying delivery of floodwater.

Physiography

Forest stormflow can differ according to physiographic region. For instance, for 137 watersheds in the Northeast, all of them 100 square miles or less in area and largely forested, the average annual number of daily discharges of more than 10 csm $ft^3/s/mi^2$ ranged from eight in northern New England to only one in the Coastal Plain (Lull and Sopper 1967).

Local stormflow can be related to elevation, which can indicate storage possibilities. At Coweeta, for example, forested primary ridges at 5,000 feet deliver almost 18 inches of direct runoff per year, whereas forest land at lower elevations delivers only 2.5 inches (Hewlett 1967b). Rainfalls of 8.4 to 10.8 inches in a December storm on three watersheds above 3,000 feet produced 5.0 to 8.8 inches of flow and maximum peaks of 68 to 167 csm. Rainfall on three watersheds below 3,000 feet was 6.8 to 7.0 inches; flow was 1.6 to 2.3 inches; and peaks were 22 to 32 csm (Hoover and Hursh 1944).

The classic stream morphological variables developed by R.E. Horton (1945) accounted for differences of 57 percent in flood peaks from large storms on southern California watershed (Anderson and Trobitz 1949, Anderson 1950). Shape of watersheds influenced annual maximum daily flow, the 10-year flood, and the annual low flow, but not the average annual flow (Anderson 1975d).

Geology

Extreme differences in flood peaks were associated with differences in both topography and geology of watersheds in the northwestern United States (Anderson and Hobba 1959). North-sloping watersheds and those having unconsolidated sedimentary rock types produced smaller floods.

Dillon and Kirchner (1975) found greater differences in water chemical quality associated with different geologic rock types in watersheds rather than between land uses.

Both annual and low flows differed greatly on northern California watersheds located on nine different geologic types (Anderson 1975d). Some types (e.g., Cenozoic nonmarine) consistently had high values for all elements of streamflow. In contrast, granitic areas produced the least annual discharge and low flows but the highest 10-year flooding. Basalt had high annual discharge and low flows, but low 10-year floods. Serpentine areas had the greatest low flows, but other streamflow characteristics were low. Different geologic types produced differences in streamflow from as little as 30 percent of average to more than three times average for daily maximum as well as for average flows. Low flows were even more varied among geologic types; granitic rocks yielded low flows only 1 to 3 percent as high as those from the basic and ultrabasic rock type (Basalt and Serpentine).

Potter (1961) found it necessary to prepare separate predictions of peak flows for zones of loess and glacial till, sandstone and shale, limestone, and schist. White and Reich (1970) showed that floods are relatively low in limestone basins in Pennsylvania.

It has been well documented that forests, along or in combination with such structures as reservoirs and dikes, do not completely prevent the flooding of great valleys, but they play an important role. Forests augment reservoir storage with watershed storage by preventing debris from bulking flood flows, and by minimizing the loss of channel and impoundment capacity by sedimentation.

Forest and Frost

The occurrence of frost in the forest in winter in the more northerly latitudes has been thought to influence several hydrologic processes. Many foresters have believed that "concrete frost"—wet soil, solidly frozen—in the forest increases flood runoff. If concrete frost should form in the forest, it could prevent infiltration and cause overland flow. This may be concluded from evidence from nonforested areas. For instance, overland flow from concretely frozen soil on open fields was a principal source of runoff in the March 1936 flood near Ithaca, New York (Spaeth and Diebold 1938). Frozen soil was only in bare fields, not in neighboring woodland or grassland. Another study reported about 80 percent of 9 inches of rain and snowmelt ran off two potato fields that had a 14-percent slope. A neighboring forested area having 27 percent slope had less than 0.5 percent of overland flow (Bennett 1937).

Apparently, concrete frost occurs only sporadically in the forest. In the Adirondacks, under maximum snow accumulation, concrete frost about 2 inches deep was present at 30 to 40 percent of sampling points in sapling stands and at 15 percent of those in sawtimber. Frost usually occurred chiefly beneath conifer crowns in the snow-interception zone (Lull and Rushmore 1961). Konda (1955) reported sporadic frost to a depth of 18 cm under hardwoods in Japan. In a hardwood stand in New Hampshire, which had numerous mounds and depressions resulting from windthrow, Hart and others (1962) noted that through most of the winter snow insulated the soil and prevented frost formation. The few points where concrete frost was observed were on mounds. They concluded that any overland flow from a mound having concrete frost would be absorbed by the unfrozen slopes and depressions adjacent to it.

In New England and the Lake States, many other studies have also shown that the frequency of concrete frost in the forest is too low to have any real effect on overland flow (Hart 1963, Bay 1958 and 1960, Striffler 1959, and Wray 1959). Most of these studies also showed that concrete frost occurs more commonly under conifers than under hardwoods, and is most prevalent in open fields.

It seems obvious that soil freezing would have effects on watershed hydrology not simply explained by the concrete frost hypothesis; soil water is immobilized, even while migrating upward to soil surfaces; a tremendous heat sink becomes established which must be dissipated, and certainly the pore space in the soil is temporarily reduced.

Thorud and Anderson's (1969) study of the forest floor as a heat sink during freezing revealed that bare soil froze 55 percent faster than litter-covered soil. A 2-inch layer of snow lengthened freezing time, but snow and dry pine litter together lengthened freezing time 54 percent over that required for the same thickness of litter alone, and 123 percent compared to snow alone. Water in the litter shortened freezing time as much as 61 percent. Therefore, we conclude that the forest floor and the soil beneath it comprise an important sink for energy, and that differences in forest floor conditions may cause significant differences in hyrologic processes.

Forestry, Erosion, and Water Quality

Probably the most current interest in hydrologic processes arises from their effects on water quality (Meier 1975). This section on hydrologic processes in relation to forestry must at least outline some of the individual water quality parameters that forestry can influence. The materials are the common particulates (inorganic and organic, living and dead), dissolved substances (inorganic and organic), amorphous substances, and gases. Radiant energy (transmitted, absorbed, and re-radiated) is also involved. These materials and influences are all reflected, somewhat inadequately, in such descriptors of water quality as turbidity, pollution, contamination, eutrophication, aeration, and water temperature. Since the hydrologic system is never in equilibrium, all measurements of its components present formidable sampling problems — and would do so even if we knew what to measure. We know how to measure erosion and its sedimentation products fairly well. We discuss erosion and its relation to water quality in detail because erosion is reported to cause 80 percent of the deterioration of water quality because products of erosion interact strongly with other components, and because erosion is directly affected by forest management.

Erosion and Sedimentation

The term "sedimentation," as used here, consists of three basic processes: erosion, sediment transport, and deposition. Erosion is the detachment and initial spatial displacement of soil, rock, or organic matter by whatever agent and in whatever state. Sediment transport is the movement of erosion products after initial displacement, and here includes movement of particles into the interstices of soil or rock. Deposition is the temporary or permanent halting of the movement of transported products of erosion.

Some characteristics of the forest system that affect erosion and sedimentation are unique among land types. These include the hydrologic properties of the soil mass, the types of terrain that the soil mass often occupies, the erosional processes and how they occur, and the high sensitivity of each process to change. Surface soil layers generally have high capacities for infiltration and percolation. Forest soils sometimes occupy slopes steeper than the natural angle of repose for the geologic material, for the soils are anchored by the tree roots. These steep slopes imply an erosional process of channel downcutting over long periods, and mass creep and occasional mass sliding from lower slopes into the channel (Anderson 1967a).

Surface erosion of forest sites usually follows intense rainstorms that follow baring of the soil by logging, fire, overgrazing, mass movement, or other causes. Landslides and mudflows may be started or accelerated by land use, but usually they too are associated with heavy rains and slide-prone conditions either in the soil mass or at the contact of the soil with the underlying rock. However, mass movements by soil creep and ocassionally by mudflows or landslides are pervasive natural processes that occur even in the undisturbed forest.

The three hydrologic processes principally initiating erosion and sedimentation are raindrop splash, overland flow, and streamflow scour. Interception may increase splash in those unsual situations where mineral soil has been exposed beneath the canopy by burning or trampling, for raindrops intercepted by a high canopy and dripping from it have greater mass and kinetic energy than ordinary rainfall (Tsukamoto 1966b) and therefore greater potential for causing splash erosion.

Infiltration capacity of forest soils is usually high. Surface erosion and transport of soil are eliminated when and where infiltration capacity equals or exceeds rainfall, snowmelt, and lateral overland flow additions. However, Ellison (1949) showed how a bare, very permeable soil having a high infiltration capacity can be practically waterproofed by the splash erosion from 20 minutes of rainfall. But high infiltration capacities can have an undesirable effect. In some localities, high infiltration builds up soil water which locally destroys cohesion of the soil mass, augments soil creep into channels, or causes mass slope movement into them; or it may cause local soil saturation and growth of channels by solifluction (mudflows). However, a recent intensive study of slope stability in coastal Oregon (Harr and Yee 1975) showed that saturated soil was rarely found, and further that natural infiltrated and percolating water did not affect the soil aggregation that was essential to slope stability. Landslide processes are discussed under Timber Harvest—Landslides.

The surface of upland forests, where mineral soil is fully protected by a cover of litter and humus, contributes little or no sediment to streams. In these forests, erosion occurs almost entirely within the major and minor stream channels; local solifluction and creep move soil to the channel, and the cutting and transporting power of streamflow detaches particles from the banks and carries them downstream. The channel then is in dynamic equilibrium with the quantity and frequency of streamflow, which control the length, width, and carrying capacity of the channel. Hansen (1970) reported a 530 percent increase in the volume of suspended sediment in a 26-mile reach of a Michigan stream, largely as a result of channel bank erosion. When infrequent high flows occur, they overtax the channel and the flow starts to widen and lengthen it. Thus in any stream, sediment must be expected in times of extremely high flow. Extreme high flows may not only produce high yields of sediment, but may create unstable channel banks; so the watershed is more vulnerable to erosion for some time to come (Anderson 1970b, 1972).

Where areas of the forest floor have been disturbed by logging, grazing, or burning, infiltration is reduced by the compactive effect of moving equipment, trampling animals, or beating raindrops, and overland flow; soil erosion can result. Loss of soil then becomes a function of soil erodibility, length and steepness of slope, and the intensity of storm rainfall.

One index of the intensity of storm rainfall is the rainfall erosion index (the product of total storm energy in foot-tons per acre-inch and the maximum 30-minute intensity, divided by 100). This index differs widely from region to region. Average annual indexes from available data range from 75 to 200 for the Northeast, 200 to 600 for the Southeast, and 50 to 250 for the North Central States (Wischmeier and Smith 1965). In the West other indexes of erosion are more useful, such as volume and peak streamflow and the frequency of rainfalls versus snowstorms. These have been shown to be related to sediment production from forested watersheds, and hence to the erosion potential of forest sites (Anderson 1954, Wallis and Anderson 1965, Anderson 1975c).

After protective litter and humus have been removed, comparative soil erodibility controls erosion. Comparative erodibility has been studied particularly in California, Hawaii, and the Pacific Northwest (Anderson 1954, Anderson and Wallis 1965, Yamamoto and Anderson 1967). In California, for example, soil erodibility varied by a factor of eight among major soil types. Soils under Douglas-fir stands in eastern Washington were 45 percent more erodible than soils developed from similar parent materials in western Washington that had twice as much organic matter in the surface 19 inches (Balci 1968). In the southern Sierra Nevada, Willen (1965) found that granitic forest soils at elevations above 6,500 feet were potentially about 2.5 times more erodible than granite-derived soils below 4,500 feet. In northern California's forest-covered mountains, soils developed from acid igneous and schist rock types were more erodible than soils from the more basic and ultramafic types; and soils developed under fir were less erodible than those developed under ponderosa pine, brush, or grass (Wallis and Willen 1963). Similarly, soils in Hawaii that developed under the native ohia were more erodible than soils developed under introduced tree species (Yamamoto and Anderson 1967). Wooldridge (1964) reported that more than 40 percent of the soil erosion hazard in central Washington could be accounted for by variation in the content of organic-matter, pH, total porosity, and bulk density of the soil.

Stoniness of watershed soils may strongly affect erosion and water quality. Analysis of sediment data from watersheds in western Oregon indicated that streams in areas having gravelly soil became armored with coarse particles and hence had fewer days of turbid flow (Anderson 1975a). Results suggest, for example, that watersheds having 67 percent stone in their soil had only about 23 percent as many days of turbid streamflow as soils containing only 17 percent stone.

Self-healing of disturbed areas can accompany the development of an erosion pavement (a layer of stones protecting the surface); however, this may be effective only after considerable damage has been done. Self-healing can be interrupted and erosion resumed by storms whose intensities exceed the infiltration capacities of the disturbed areas.

The dominant erosion processes differ considerably between watersheds, within management units, and over time. Mass movements, such as landslides, have accelerated erosion in areas considered to have recovered from logging (Fredriksen 1970). Within watersheds, unstable slope and soil combinations have been identified (Wallis 1963). The consequences of these differences in erosion potential on sediment yield and water quality are outlined under regional hydrologic characteristics affecting forestry and water. Interactions between sediment and other characteristics of water quality are discussed under each of those characteristics.

Although sediment is considered to be the most important single factor in limiting water quality, forest management also affects other factors that influence water quality.

Water Temperature

The forest influences the temperatures of soil water and streamwater by affecting the paths that water takes, by shading the ground and the stream, and by using energy for evaporative cooling. Management that changes any of these influences can change water temperature.

Raising water temperature may have both good and bad results; the balance depends on the particular stream situation. Warmer temperatures favor food production, which is all too small in many trout streams. If temperature of the stream is already near the upper threshold favorable for trout, opening the forest along the stream channel may be detrimental. The best trout fishing is in streams whose maximum temperatures never exceed 60 to 68° F. Water temperature for warm-water fish should not exceed 93° F at any time or place (Tarzwell 1960). Indirect effects of increased temperature include effects on dissolved oxygen. At elevated temperatures decomposition of organic debris in streams may deplete oxygen below critical levels for fish (Berry 1975).

Brown (1969) and Edinger and others (1968) have recently studied in considerable detail the microclimate of water surfaces and the heat balance in flowing streams. Brown reported wide differences in the amount of heat absorbed by flowing streams and stream bottoms. Bedrock bottoms absorbed as much as 25 percent of the energy, but gravel bottoms apparently were an insignificant energy sink. He reported differences of as much as 11° in May in temperatures of shaded and unshaded streams. Winter exposure of streams and their margins may be important to water storage. Walter T. Wilson, in a personal communication about 1947, attributed the temporary reductions of groundwater contributions to streamflow to freezing at stream margins. The formation of frazil ice in streams has also been related to the rate of cooling; here, too, the insulating effect of the forest may play a significant ameliorating role.

On the other hand, the biological productivity of streams that are too cold may be increased by raising stream temperature through much the same techniques as snowmelt is managed—cutting shade to the south while leaving trees on the northern stream margin to provide back radiation. Berry (1975) has modeled the effects of streamside clearing length on stream temperature. Biological productivity also can be affected by sediment in streamflow, for light penetration may be reduced so much as to inhibit growth of beneficial microorganisms.

Water Chemistry

Dissolved solids, most of which are essential nutrients in the forest ecosystem, are another element of water quality. In the mature forest the nutrient cycle generally approaches a steady state, and only small amounts of nutrients are discharged in the drainage water. As a result, volumes of dissolved solids are usually small in streamflow from forested areas and primarily reflect the geology of the area (Foggin and Forcier 1974, Dillon and Kirchner 1975).

The forest floor and forest soil have remarkable absorptivity. This was most notably demonstrated in a (1959-61) study at the Central Sierra Snow Laboratory of radioactivity associated with atomic bomb fallout. Radioactivity was measured in incoming precipitation, in the snowpack, and in the snowmelt streamflow. In incoming precipitation, radioactivity reached as high as 50 times the water quality standard, and it was as high as 10 times the acceptable standard in the whole 10-foot-deep snowpack. Radioactivity in the streamflow from the snowmelt approached the standard of 1000 micromicrocuries per liter on only one day; usually it was on three-tenths of the standard or less. Public Health officials concluded that the forest floor and surface soil had absorbed most of the radioactivity. This may help to explain the ability of the forest to remove biological pollutants (Nikolaenko 1972, 1974) and chemicals that are applied in forest treatments.

Management practices affect the chemical quality of water by influencing the type of vegetation and rate of growth (thus affecting uptake), the amount and rate of deposition on the forest floor (as by production of logging slash or the removal of forest products), and the rate of decomposition of organic matter (by changing the exposure, temperature, and moisture content of the forest floor). Any treatment that changes the volume of streamflow may influence the removal of dissolved solids from the system in the drainage water, especially if surface soil, which is highest in such nutrients as nitrogen, erodes.

Of all pollutants dissolved in water, nitrogen deserves greatest attention in forest management (Tarrant 1972). In coastal Oregon, the total nitrogen in precipitation throughfall was nearly five times greater under the hardwood *Alnus* species than in rainfall not intercepted by forest canopy. Nitrogen was three times greater under conifers than in nonforested areas. The annual addition of nitrogen to the forest floor was as much as 100 lbs/acre (Tarrant and others 1969); so, for approximately 60 inches of precipitation, the concentration of nitrogen was about 7 p/m.

Natural addition of organic materials directly into the stream may temporarily degrade water quality. Slack and Feltz (1968) showed that water quality in a small stream was related to the autumn leaf-fall from reparian vegetation over the stream channel. Dissolved oxygen and pH decreased; water color, specific conductance, iron, magnesium, and the bicarbonate ion increased as the rate of leaf-fall increased. Stream quality improved rapidly after the channel was flushed by stormflow. Organic matter in the stream has benefits also, because it is a primary source in the chain of food production.

Forest practices that affect nutrients and other water quality characteristics are discussed later in the section Management for Water Quality.

Integrating Hydrologic Processes

How do we assemble the data on processes to predict water yield, floods, erosion, and sedimentation?

That depends on how each process relates to the objectives and on what technique is appropriate for predicting (Australian Academy of Science 1975). The two general classes of techniques, simulation and multivariate analysis, have somewhat different objectives. Use of both techniques has been greatly facilitated by developments in computer technology. Simulation as applied in hydrology is essentially a bookkeeping technique—individual hydrologic processes act sequentially on such an input as precipitation, and the summed results are routed to give an estimate of outputs varying with time. Notable working models include those by Crawford and Linsley (1964), Riley and others (1968), and Dawdy and others (1972). Many variations and extensions are constantly being reported. Essentially, the simulation technique relies on a satisfactory ability to evaluate the operation of hydrologic processes in space and time. The model can always be modified so that it will predict in a particular circumstance, but no greater insight into hydrologic processes seems to have come from the applications of simulation models.

Recent simulation models that deal with forest hydrology output include the Leaf and Alexander (1975) model, which integrates research results from Colorado into predicted outcomes of different cutting patterns. Galbraith (1975) has developed a method for predicting increase in water yield from timber harvesting for use in northern Rocky Mountain forests. In the Pacific Northwest, Ryan and others (1974) have reported development of an ecosystem model that includes forest hydrology outputs.

Other simulation models aim at evaluation of particular management practices, such as prescribed burning (Agee 1973), or timber harvest (Belter 1975), or water quality (Willis and others 1975), or particular outputs, as flood peaks (Dawdy and others 1972, Fogel and others 1974), or even particular processes as soil moisture (Zahner 1956). Each modeler has his own version of someone else's model, having made necessary modifications to fit his own data available or own needs for predicting outcomes. Lombardo (1973) has concluded that there are no satisfactory models for water quality; the modeling by Willis and others (1975) seems to have promise in this difficult modeling development.

In contrast to simulation, multivariate analysis results have other uses in addition to prediction (Wallis and Anderson 1965, Lull and Anderson 1968). This type of analysis can determine the potential of unit areas of forests to produce particular water products (Anderson 1975d). It may relate a product to a cause having known frequency, and it can test the significance on a variable's effect on the product. Once the model is developed, independent variables may be manipulated to test the consequences of alternative possibilities in land management and to select the most desirable outcome.

The first applications were simple; many of them dealt with peak flows. Multiple correlations and regression were used to relate meteorological, topographic, and other watershed variables to peak discharges of storms, mean annual flood peaks, or peak flows of rare large storms. In 24 states where studies have been made, the principal hydrologic factors that are significantly correlated with the mean annual flood are drainage area, shape of basin, type of soil, and area of lakes (Benson 1962a). Annual peak discharges in New England were related principally to area of drainage, main-channel slope, and storage in lakes and ponds (Benson 1962b). Annual peak discharge of floods in Texas and New Mexico was related to drainage area, rainfall intensity, main-channel slope, storage, mean annual precipitation, and altitude (Benson 1963). In Northeastern watersheds, Lull and Sopper (1967) found that the highest mean daily discharges (at 0.1 percent flow durations) were related to precipitation intensity, slope, and percentage of area in swamps, but were not related to percentage of forest-covered area.

For small watersheds in most of the United States east of the 105th meridian, Potter (1961) related the maximum annual peak (equaled or exceeded on an average of once in 10 years) to drainage area, precipitation, topographic indexes, and drainage density. In an earlier study Potter (1953) had reported similar findings based on analysis of 51 watersheds in the Allegheny-Cumberland Plateau; he noted that the percentage of area in cropland, pasture, or woodland had no effect on the magnitude of the 10-year peak. He based this conclusion on his regression of peak flows versus area, for many of the largest deviations above the regression had 98 percent woodland, whereas those below had 50 to 60 percent cropland (hardly a conclusive technique).

On the other hand, Reich (1972) found that increased percentages of wooded area reduced flood magnitudes in Pennsylvania, at least those of 2.33-year return period; he concluded that the percentage of wooded area is a more important determinant that many geomorphic parameters of regional flood prediction equations. Peak discharges from watersheds in the Northwest have been related to several meteorologic, topographic, geologic, and forest-cover variables. The age and stocking of the forest below the snowmelt line during a storm were related to rain-snowmelt floods; snowmelt floods were related to the area of poorly stocked and burned forest (Anderson and Hobba 1959).

We conclude the discussion of classical hydrologic processes, their modifiers, and some of their applications realizing that, in almost all forest situations, the spatial distribution of many of these processes may differ greatly from these classic models. For example, water moving downslope in both saturated and unsaturated flow is effective in extending the period when water is available for transpiration to the forests on lower slopes, adjacent to channels, and at locations with shallow or impervious strata (Tsukamoto 1966a). Almost all experimental measurements of water use from watersheds have indicated greater use than would have been predicted from measurements of soil-water depletion and interception.

Martinec (1975) reported from a study of tritium content of subsurface flow that outflow from the watershed represented water hitherto in subsurface storage for "a number of years." Infiltrated water on the watershed was substituted for, perhaps by some pressure wave phenomena, (Vischer 1970 quoted by Martinec 1975).

Forests through their effect on the distribution of falling rain, on distribution of snow, on freezing of the soil, and on the production of ice lenses within snowpacks, create situations of highly varied water percolation, typically under conditions quite difficult to measure quantitatively. It will become evident that these spatial and time variations of soil moisture have implications not only for management for water yield from forest but also for control of flood flows and sedimentation.

II - FOREST TREATMENT AND WATER

The hydrologic response—water yield, floods, and water quality—to forest treatment depends on the characteristics of the forest, the nature of the treatment, and the posttreatment recovery of those watershed attributes that affect the hydrology. The forest itself may be characterized by such attributes as type, age, and density, or by more fundamental measures such as basal area or biomass, or measures that attempt to characterize the whole forest ecosystem. The treatments themselves vary widely, from harvesting, prescribed burning, grazing, and planting, to the havoc wrought by insects, diseases, winds and wildfires. The extent to which the forest's influence is altered depends on the intensity of treatment or assault. The greatest effects are usually produced by clearcutting, intense burning, heavy grazing, intensive planting, catastrophic attacks by insects and diseases, and blowdown. The size of the area—and the proportion of the watershed—subjected to the treatment or assault often have primary importance.

Some effects are influenced too by climate, soils, topography, and geology. They differ by season of the year, and are influenced not only by a specific forest happening but also by what occurred before and after it: how long recovery takes, the nature of replacement vegetation, and so forth. Thus the subject is complex. Presentation here is in terms of qualitative effects on hydrologic processes illustrated by some quantitative examples.

Timber Harvesting

Timber harvesting includes severing trees from their stump, cutting the bole into sections, and removing the timber from the watershed. Construction and use of skidtrails and logging roads is usually an integral part of the harvesting operation, which may also include burning or other disposal of the slash. The impact of timber harvesting on the water resource depends upon the severity of the changes in vegetal cover, the exposure and compaction of the mineral soil, and the proportion of watershed affected (Megahan 1972, Stone 1973). It is also influenced by the rate at which soil and vegetation recover, either by natural reproduction or by the planting of woody and herbaceous species. Timber harvesting affects the water resource by its influence on the fundamental hydrologic processes.

Interception

Interception of precipitation by deciduous hardwoods is not greatly reduced by forest cutting; logging residue (stumps, branches, and foliage) and the remaining understory continue to intercept moisture. If the area is to remain in the forest cover, revegetation within 10 years can restore much of the interception. Partial cutting in hardwoods has little effect on snow interception. In northern Minnesota, for example, maximum snow accumulations in four aspen stands thinned to 50, 65, 80, and 115 square feet of basal area were 4.5, 4.1, 4.2, and 4.3 inches of water respectively (Weitzman and Bay 1959).

On the other hand, interception by conifers may amount to as much as 30 percent of annual precipitation; therefore, interception by conifers may be reduced more by forest cutting than it is in hardwoods. Such reduction can substantially increase streamflow. Regeneration of conifers is not initially as rapid as the resprouting of hardwoods. It may take 20 to 40 years in the East and 50 years or more in parts of the West for a cutover stand to even approach full interception.

Snow Accumulation

Snow accumulation is markedly affected by timber harvesting; increases in the maximum snow accumulation in four western states after heavy cutting ranged from 22 to 40 percent (*table 6*). Light cuttings increased snow accumulation by 10 to 17 percent. In Minnesota, percentage increases were much larger because snow accumulations were small. The greatest absolute increases, up to 19 inches in terms of water equivalent, have been in the deep snowpacks of the central Sierra Nevada of California, where both interception and winter snowmelt were involved.

Often excess snow in openings is a redistribution of snow, and it is partly balanced by a decrease under the trees (Hoover and Leaf 1967, Hoover 1971, 1973). Anderson and Gleason (1959) reported that one-half of the 13 inches (water equivalent) of greater amount of snow found in a cut strip was in effect "stolen" from the forest to

Table 6–*Increase in maximum snow accumulation (water content) after cutting in western conifer forest*

Location and forest cover	Treatment	Maximum increase in snow accumulation	
		Inches	*Percent*
(1) Fraser Exp. Forest, Colo.	Uncut: 11,900 fbm	0.0	
	Cut (residual volume):		
Mature lodgepole pine	6,000 fbm	.81	12
	4,000	1.01	15
	2,000	1.49	21
	0	1.99	29
Young lodgepole pine	Heavy thinning (reduction from 4,400 to 630 trees per acre)	2.3	23
	Light thinning (reduction from 4,400 to 2,000 trees per acre)	1.7	17
Mature Englemann spruce-subalpine fir	Removal of 60% of volume by strip cutting and group and single-tree selection	2.8	22
(2) Front Range, Rocky Mountains, Colo. Ponderosa pine and Douglas-fir	Selection cut	.45	6
	Commercial clearcut	1.21	29
(3) North Central Wyo. Lodgepole pine	Clearcut blocks	2.5	40
(4) Willamette Pass, Oreg. Mountain hemlock and true fir	Strip-cut, strips 2 chains wide	5	15
(5) Central Sierra Snow Laboratory, Calif. (NE) Red fir	Clearcut	11	23
	East-west strip, 1 tree-height wide	12	26
	Block cutting, 1 tree-height wide	15	34
	Selective cutting; crown cover reduced from		
	90% to 50%	2	5
	90% to 35%	9	19
	Commercial selection cut	7	14
	Wall-and-step forest	19	25
(6) Minnesota Black spruce	Single-tree selection	.1	4
	Shelterwood	.7	28
	Clearcut strip	1.5	60
	Clearcut patch	2.0	80

Compiled as follows: (1) Wilm and Dunford 1948, Love and Goodell 1960; (2) Berndt 1961; (3) Berndt (1965; (4) Rothacher (1965b; (5) Anderson 1956, 1963, Anderson and others 1958, Anderson and Gleason 1960; (6) Weitzman and Bay 1959.

the leeward. On the other hand, the study of snow in 36 natural openings showed greater amounts in both forest openings and the forest adjacent to openings than in the continuous forest (Anderson and West 1966, Anderson 1967b). Snow in openings melts more rapidly than snow within the forest, and this can increase or decrease peak flow, depending on synchronization with melt elsewhere on a watershed.

Haupt (1973) reported the role of snow accumulation in relation to wind and surface exposure near major ridges, and suggested cutting forest on the windward side to store snow to the lee.

Surface Detention

Logging, land clearing, or fire may reduce roughness of ground or stream channel and thereby increase the speed of flow in saturated areas and in channels. Timber harvesting that augments accumulation of snow may increase detention capacity in the snowpack. Detained water may have contradictory effects when the snow melts, depending on the timing and the location of the snowpack in which the additional water was detained. Forests at high elevations, cut or uncut, may have sufficient detention capacities for rain and slow snowmelt in early season. At intermediate elevations, forest cutting usually allows the rapid ripening of snowpacks, especially on south slopes. Detention storage capacity during rain on snow is lost and melt is speeded (Anderson and Hobba 1959); exposure of snow surfaces in openings may speed melting by increasing latent heat exchange from the moist atmosphere to the snow (Anderson 1969). At lower elevations, the speeding of snowmelt by forest removal may help to desynchronize peak flows from different parts of the watershed (Satterlund and Eschner 1965).

Other than surface detention in snowpacks, timber harvesting may cause small difference in detention on the soil surface, as in pondage in skidtrails, behind road fills, and in stump depressions resulting from whole-tree logging. Most of these effects have not been separately evaluated.

Infiltration, Overland Flow, Erosion, and Sedimentation

These four processes are discussed together because when infiltration capacity is sufficiently reduced, overland flow and erosion usually follow. Erosion of soil provides material for sediment in the stream, although not all the eroded material reaches the stream and some of the sediment comes from the channel area rather than from the land surface.

Merely cutting trees does not affect infiltration capacities. The generally high rates of infiltration characteristic of the forest remain after harvesting except where logging activity has exposed the mineral soil or caused soil compaction. The influence of the organic layers and the forest soil structure persists for some years after cutting; when regrowth is reasonably prompt, new organic contributions are provided to maintain soil stability, which prevents degradation.

Clearcutting mature hardwoods at Coweeta (Hoover 1945) produce no overland flow and consequently no erosion. Cut trees were left where they fell, and a heavy ground cover rapidly developed. At the Hubbard Brook Experimental Forest, felling the trees and treating with herbicide to eliminate ground cover (a treatment for research purposes only), increased sedimentation fourfold during the next 2 years, from 8.6 to 34 tons per square mile per year (Pierce and others 1970). Apparently there was no overland flow, and the additional sediment came from the stream channel.

Harvesting reduces infiltration capacity to the extent that forest soil is exposed and compacted by roadbuilding, skidding, and hauling. Careful logging may disturb no more than 10 percent of the area; overland flow resulting from reduced infiltration may then be of little consequence. In contrast, careless logging can compact and disturb as much as 40 percent of an area, reducing infiltration from several inches per hour to a fraction of an inch, and generating damaging overland flows from high-intensity rainfalls. Murai (1975) reported that infiltration in a cutover forest that was heavily disturbed was about 1 inch per hour—only 20 percent of that in the uncut forest.

In some situations, erosion is relatively easy to control. Logging on coarse-textured, permeable soils in the front range of the Rockies, with careful roadbuilding, has produced little sediment (Leaf 1966). The essential stability, despite heavy cutting, of the glaciated soils of New England's forested mountains also has long been recognized (Cleland 1910).

Elsewhere the situation can be quite different. On clay soils at Coweeta, roads and logging produced maximum sediment concentration in streams of 7,000 p/m as compared to 80 p/m for an undisturbed area. Turbidity from the logged area averaged 93 p/m compared with the 4 p/m from the check area. Repeated measurements of road cross sections showed that in 4 years the 2.3 miles of road lost 6,850 cubic yards of soil (Hoover 1952). This impaired water quality of the stream that drains an 1,880-acre watershed so severely that the timber value was judged to be less than the cost of treating the water (Hursh 1951).

Surveys of eight major basins in southeastern states reported that logging activities were responsible for more than half of the increases in sediment production from forest lands in seven of the basins (Dissmeyer 1976).

In Arizona, logging and road construction increased sediment yield from a 248-acre watershed from 3.5 tons annually to 21 tons from only two summer storms and 57 tons from two winter storms (Rich and others 1961). Before logging, a certain 2,500-acre watershed in the Sierra Nevada yielded 0.4 ton of sediment per acre per year. The first year after a commerical selection cut of one-fourth of this watershed, the logged area yielded 6.1 tons per acre; in the following year it yielded only 1.8 tons (Anderson 1963). Increases in concentrations of sediment were associated mostly with the high discharge classes: the highest 12 percent of the streamflow carried 60 percent of the sediment. Sedimentation rates dropped rapidly after logging. For a high discharge class of 55 to 79 ft^3/s, the rate before logging was 20 p/m; during the first, second, and third years after logging, the rates averaged 190, 90, and 45 p/m (Anderson and Richards 1961).

Logging roads—Logging roads and their unprotected cuts and fills are a primary source of sediment from forested watersheds. Movement of sediment downslope from a road depends on the amount and velocity of runoff, the availability of erodible soil, and the obstructions to sediment transport (Haupt 1959). Road cuts can produce tremendous quantities of sediment, depending upon their slope and aspect.

In south central Idaho, three adjacent watersheds with highly erodible granite-derived soils produced sediment yields of 12,400, 8,900, and 89 tons per square mile in one season following construction of logging roads. Watersheds without roads yielded no measured sediment (Copeland 1965).

A similar relationship was found in the analysis of 29 watersheds in western Oregon: an increase in the annual timber cut from 0.6 to 1.5 percent would increase sediment loads an expected 18 percent; increasing total road area from 0.1 to 0.55 percent would increase sediment loads 260 percent (Anderson 1954).

In central Idaho, during a six-year study, the effects of skyline logging with no roadbuilding were compared with those of jammer logging. (The jammer has an A-frame with winch and cable mounted on a truck; it requires closely spaced roads.) Skyline logging with no roads increased sediment deposition by only 1.6 times; in contrast, jammer-logging with numerous roads, which may disturb 25 percent of an area, increased deposition by 850 times for the 6 years after road construction (Megahan and Kidd 1972, Megahan 1975).

Gradual reduction of road-induced sedimentation has been observed on some watersheds; however, Megahan (1975) believes that full recovery in central Idaho may not be expected. A watershed crossed by a 37-year-old road, apparently fully stabilized, still produced twice as much sediment as similar but unroaded watersheds. Historically, roads often have been upgraded from dirt to surfaced roads, typically with major realignment; such upgrading may be beneficial in midslope locations, but highly detrimental in increasing sedimentation from streamside roads (Anderson 1974). Roads in steep watersheds show twice as much increase in sedimentation as roads in moderately sloping watersheds (Anderson 1976).

In the Douglas-fir region, only one-third of the area of a typical road is occupied by the roadbed; cut and fill slopes cover the remainder of road area (Dunford 1962). Forest roads in the Intermountain region have about 8 acres of cuts, fills, and ditches for every mile of road (Usher 1961). In Mississippi, sawtimber harvesting disturbed 15 percent of logged areas; 5 percent was contributed by roads, 7 percent by skidtrails, 2 percent by log movement, and 1 percent by landings (Dickerson 1968).

Under some conditions, sediment production from logging roads can be both substantial and prolonged. After 1.7 miles of road were built on 6.2 percent of a 250-acre watershed at the H.J. Andrews Experimental Forest, the first storm of the rainy season produced a turbidity (suspended sediment concentration) of 1,780 p/m, 250 times the concentration in the undisturbed watershed. Sediment concentrations remained high during the first 2 months of the rainy season, and during the next 2 years they continued at about twice the concentration measured before road construction (Fredriksen 1965b).

The degree of disturbance and consequent erosion and sedimentation differ widely according to the erodibility of soil, the intensity of the timber cut, the care used in logging, and the type of equipment used.

There is considerable evidence that careful logging minimizes sediment production. Successful erosion prevention or control depends on the care and skill used in skidding and hauling the timber products and in the construction and maintenance of trails and roads used for these purposes. Failure to close substandard roads after logging—leaving them for recreational or other use—can indefinitely prolong erosion and production of sediment.

Less soil is lost from high-quality roads than from less well built roads. At Fernow Experimental Forest, sediment production per unit length for a good road (of moderate slope and with drainage provided) was only about half that for a poor road (with no restriction on grade and no drainage provided) (Weitzman and Trimble 1952). The greater the use of skidroads, the greater the soil loss. Heavily used skidroads at the Fernow lost 3.7 inches of soil during skidding; lightly used roads lost only 1.0 inch (Trimble and Weitzman 1953). Of course, both of these rates would produce high turbidity if the lost soil reached a stream.

The density and grade of roads may be significantly reduced by adequate planning. Logger's-choice road system (unplanned) at the Fernow Experimental Forest occupied 4.8 to 7.0 percent of the area and had grades of 14 to 24 percent; a planned system occupied 2.5 to 4.6 percent and had grades of only 9 to 15 percent. Careful planning reduced the area in skidroads by 40 percent and eliminated steep grades (Mitchell and Trimble 1959).

Care in constructing road drainage is needed in areas where slopes are unstable; Harr and Yee (1975) suggest that drainage from culverts can destroy soil aggregation necessary for natural stability of slopes.

Another study at the Fernow showed that amounts of erosion and sedimentation resulting from logging 50-year-old hardwood stands were closely related to the severity of soil disturbance, which in turn depended principally on the care used in laying out and draining skidroads. Logging 86 percent of the timber volume with no road plan and no provisions for drainage resulted in a maximum turbidity of 56,000 p/m; 38 percent of all samples had more than 10 p/m. Logging 20 percent of the timber volume using careful road planning and provision for adequate drainage produced a maximum of 25 p/m, and only 1 percent of all samples had more than 10 p/m. Meanwhile, the unlogged control watershed showed a maximum of 15 p/m, but almost all samples registered less than 10 p/m (Reinhart and others 1963).

This study emphasized how quickly sedimentation diminished after logging. Streamflow from the most heavily eroded watershed averaged turbidity of 490 p/m during logging; within the first year after logging this dropped to 38 p/m, and in the second year to a negligible amount (Reinhart and others 1963).

A later clearcutting operation on the Fernow (Hornbeck 1967), for which skidroads were carefully laid out, drained, and maintained, yielded streamflow with a maximum turbidity of 83 p/m, with 95 percent of the samples (taken periodically) having turbidities between 0 and 10 p/m. This study demonstrated again that, with care, these forested watersheds can be clearcut and the products removed without seriously increasing stream turbidity. Hoover (1952) pointed out that ordinary logging procedure at Coweeta produced more sediment: an average turbidity of 93 p/m compared with 4 p/m from an unlogged watershed; maximum turbidities were 7,000 and 80 p/m, respectively.

On an 800-acre timber sale on the Chattahoochee National Forest in Georgia, careful logging produced an average suspended sediment content of 5 p/m as compared to 4 p/m from an unlogged watershed (Black and Clark 1958).

Vogenburger and Curry (1959) reported that during 10 years of logging on the Waynesboro, North Carolina, 8,000-acre watershed, 50 miles of road were built and 13 million board feet of timber were harvested—all without damaging the water resource. Sediment yields from a carefully logged watershed on the Fraser Experimental Forest in Colorado increased to about 100 tons per square mile the first year after logging; annual yields in the next 8 years ranged from 65 tons to negligible accumulations. However, over an 8-year period, starting with the year of logging, a statistical comparison showed no difference in mean annual sediment yields between the logged watershed and two nearby undisturbed watersheds even though timber harvesting increased streamflow by 25 percent (Leaf 1966). In California, good logging showed no detectable increases in sediment discharge, independent of effects of road building and increased streamflow; for similar watersheds poor logging showed increases in sediment discharge of about 19 percent for each percent of watershed area so logged (Wallis and Anderson 1965). Sediment discharge increased also with increased total streamflow brought about by such activities as road clearing or logging. In northern Idaho, Snyder and others (1975) reported that clearcut logged and slash burned areas produced increases in filterable solids of 4 to 14 times that from unlogged areas. A moratorium on logging and road construction and a watershed rehabilitation program in the upper half of the South Fork of the Salmon River in Idaho since 1965 has been associated with a decrease in fines in the downstream river channel (Platts and Megahan 1975).

The area disturbed by logging with several types of equipment has been studied *(table 7)*. Since these studies were not conducted and reported uniformly, strict comparisons cannot be made. They do show, however, that tractor logging disturbed (either quite severely or of a severity not designated) from 3 to 31 percent of the area; the various types of cable logging caused similar disturbance on only 2 to 16 percent of the area. Megahan and Kidd (1972) reported that in Idaho substitution of skyline logging for the jammer could reduce disturbance by road construction by 75 percent. In the Pacific Northwest, skyline crane logging requires only about one-third the roads necessary for high-lead logging (Binkley 1965).

Skyline crane logging disturbs soil even less than high-lead logging (Dyrness 1967b, Ruth 1967). The skyline crane yards logs from steep slopes with minimum road construction. Its pattern of soil disturbance is less conducive to erosion because its skidtrails are mostly across rather than up and down the slopes. The disturbance it creates is shallower and more evenly distributed than that created by the high-lead system (Ruth 1967).

Balloon logging disturbs soil even less than skyline crane logging (Dyrness, cited by Rice and others 1972), but logging by helicopter disturbs soil the least of all (Binkley, cited by Rice and others 1972).

Landslides—Road construction and tree cutting sometimes trigger landslides. Thirty-four of 47 mass soil movements during the winter of 1964-65 at the H. J. Andrews Experimental Forest in Oregon were found along roads, although only 1.8 percent of the total area of the forest was in road rights-of-way. Movements were attributed to backslope, fill, or drainage failure. Along the 1.7 miles of road, there were 34 individual mass movements, totalling 185,000 cubic yards of earth (Dyrness 1967a). Wide differences in slide frequency were associated with geologic rock types in the area (Swanson and Dyrness 1975).

Croft and Adams (1950) attributed landslides in the Wasatch Mountains of Utah to loss of mechanical support from root systems cut and burned, and to some extent damaged by excessive livestock grazing. In southeastern Alaska near Ketchikan, the number and acreage of slides increased 4½ or more times after logging began in 1953 (11 slides during the 100 or more years before logging, 68 slides in 9 years during and after logging). Most slides occurred after 1959; the 6-year lag perhaps reflected the time required for root decay. Road construction caused slope failure at several locations (Bishop and Stevens 1964). Nakano (1971) discussed resistance to uprooting as an index of landslide control. He observed that planted trees become more effective as they get older, but that the effectiveness of roots of tree stumps declines with passing time. Trees reach half-effectiveness at about age 30 years; stumps decline to half-effectiveness in 8 years after logging.

Soil and rock movement and sedimentation during a slide may be spectacular. Fredriksen (1963) described one at the H. J. Andrews Experimental Forest, apparently triggered by rain, snowmelt, a road, and a culvert. This slide carried streambed gravels equivalent to 10 cubic feet (about 0.5 ton) per acre and suspended sediment equivalent to 1.1 tons per acre through the channel. Three years later a much heavier rain-on-snow storm deposited about 3,000 cubic feet per acre of gravel, rock, and logs in the stream channel—300 times the amount measured in the 1961 slides.

In the interim, almost one-third of this watershed had been logged by a high-lead system and then the slash was burned. One of two adjacent areas on this watershed was an uncut control. On the other one, 75 percent of the timber had been harvested by a skyline crane (Fredriksen 1965a). During the 1960-68 period the area logged by high-lead (6 percent was covered by roads) and then burned produced 109 times as much sediment discharge as the uncut control, and the area harvested by skyline crane produced only 3.3 times as much sediment as the control (Fredriksen 1970). Slope failures were involved in this sedi-

Table 7—*Area disturbed by logging, for various locations, types of cutting, and equipment*

Location and forest type	Cutting	Equipment and percent of logged area affected
(1) New York and Quebec Spruce	Commercial clearcutting	Skyline crane: skidtrails scattered and not continuous; no water concentration
(2) West Virginia: Appalachian hardwoods	All types	Tractor: Planned skidroads 2.5 to 4.6 Unplanned skidroads 4.8 to 7.0
(3) Illinois: Hardwoods	Selective cutting, about 50% volume	Tractor: Log lengths 31 Tree lengths 18
(4) Mississippi: Southern pine	All types, for saw-logs and pulpwood	*Litter* *Bare soil* Wheeled tractor 4 13 Crawler tractor 6 8 Mule team 6 6 A-frame, cable 4 8
(5) Idaho: Ponderosa pine	About ¼ to ½ volume: single-tree and group selection	Tractor: Single tree 3 to 18 Group 3 to 13
(6) Washington: Douglas-fir	Clearcutting	Tractor: 26 in skidroads
(7) Washington: Ponderosa pine Douglas-fir	 65% volume 81% volume	*Deep soil* *Shallow soil* Tractor 15.9 6.3 Skyline crane 3.2 2.2
(8) Eastern Oregon and Washington: Ponderosa pine	Crown density reductions of 48% to 67%	Tractor: 22 (bare)
(9) Eastern Oregon and Washington: Ponderosa pine	54% of board foot volume	*Deep soil* *Shallow soil* Tractor 15.0 5.9 Cable 1.9 13.3 Horse 2.3 9.5
(10) Oregon Douglas-fir, western hemlock	Clearcutting	*Disturbed* *Compacted* Tractor 62 27 High-lead 40 9
(11) Oregon: Sitka spruce, western hemlock	Clearcutting	High-lead: 16 (bare) Skyline crane: 6 (bare)
(12) Oregon: Douglas-fir, western hemlock	Clearcutting	High-lead: 14.8 (bare) Skyline crane: 12.1 (bare)
(13) California: Sugar and ponderosa pines, white fir	40% to 90% volume	Tractor: 22 (bare)

Compiled as follows:

(1) Fobes 1950
(2) Mitchell and Trimble 1959
(3) Herrick and Deitschman 1956
(4) Dickerson 1968
(6) Steinbrenner and Gessel 1955
(7) Wooldridge 1960
(8) Garrison and Rummell 1950; 1951
(9) Garrison and Rummell 1950; 1951
(10) Dyrness 1963'
(11) Ruth 1967
(12) Dyrness 1967b
(13) Fowells and Schubert 1951

mentation. The first slide originated from soil spilled over the hillside below a road being constructed. Thirty-two other landslides occurred in the patch-cut watershed during the storm in December 1964; all but three were adjacent to stream channels. No landslides occurred in the uncut control watershed.

Landslides are not so serious a problem in much of the East as in parts of the West. Flaccus (1958) concluded that the slides he studied in New Hampshire were not appreciably affected by logging or road construction.

A Logging-Flood-Sediment Interaction—Predicting expected increases in sedimentation after logging may be complicated by weather variations. Studies have shown that watersheds may produce much more sediment in years immediately following a major flood especially when the areal extent of major storms coincides with watershed areas harvested by improper logging methods, or by inadequately designed roads (Anderson 1970b). For example, the first year after the December 1964 flood in north coastal watersheds of California, sediment production increased by as much as 33 tons per acre. Sedimentation the first year *after* this flood was as much as five times the preflood amount. Analysis of records from 31 watersheds after such major floods showed that the sediment increases were associated with topographic differences, the size of the flood in the individual watersheds, and the past land use in watersheds; these differences also affected the time to recovery from the major flood effects on sedimentation.

The major result of that study (Anderson 1970b) was the evidence that poor logging practices, such as locating roads adjacent to streams and landings in draws, caused increased sediment concentration *after* the floods. Contrasting two watersheds, one with the average amount of poor logging (19.2 acres per square mile or 3 percent of the total area) and the other with no logging, the watershed with the combination of poor logging and a large flood had a 70-percent greater increase in sediment after the flood. The increases in sediment discharge were greatest on the steepest watersheds and on those at higher elevations. Increases in sediment discharge lessened each successive year after the flood; however, the return to normal conditions can be slow.

There is no question that poor logging increases sedimentation by several times the normal. The rate of watershed recovery after a combination of poor logging and major floods was analyzed by the regression of annual sediment yields of some northern California watersheds. This analysis indicated that 10 additional years would be required for recovery of a watershed subjected to poor logging over 100 percent of its area and to the impact of the 1964 flood (Anderson 1972).

Evapotranspiration

Evapotranspiration may be reduced in proportion to the area of the timber stand which is cut. The reduction integrates reduced interception, reduced transpiration from the canopy, and a small increase in evaporation from the more exposed forest floor. The reduction occurs principally during the growing season. Clearcutting may also increase snow evaporation—in California, for instance, from about 0.6 to 2.6 inches, depending on exposure (West 1962).

Evapotranspiration is rarely measured directly. Aerodynamic or mass and energy budget techniques have not been widely used in evaluating forest harvest effects on evapotranspiration, chiefly because of the sampling problems involved. Our information on how timber harvesting influences it is gained mostly from the measurement of changes in soil-water storage and streamflow.

Soil-Water Storage

Both storage capacity, at least to a slight extent, and storage opportunity can be reduced by cutting trees. Capacity is reduced proportionately as soil organic matter and accumulations of forest humus are reduced. Where regrowth is rapid, as noted, this can be only a minor effect. Storage capacity and opportunity are also reduced where the forest floor is transformed to roadbed or skidtrail; usually this is only a small percentage of the harvested area.

However, in the whole logged area, the opportunity for storage may be greatly reduced during the growing season and for some time after it. For example, Ziemer (1964) found that in early September, when moisture depletion is maximum in red fir on the western slopes of the Sierra Nevada, forest openings 1 year old had 6.9 inches less storage opportunity per 4 feet of soil than the surrounding forest. With regrowth the difference rapidly diminished: 2.9 inches at 5 years, 1.2 inches at 10 years, and negligible differences at

16 years. Reduction of storage opportunity, of course, is water "available for streamflow" in the succeeding year (Wilm and Dunford 1948).

Shallow soils undergo little change in soil-water storage opportunity, because regrowth or a replacement ground cover dries the soil readily, using about as much water as the original forest cover did.

Duration of the effect of clearcutting is related to soil depth. Seven years after commercial clearcutting of a shallow-soil watershed at the Fernow Experimental Forest, 78 percent of the original increase in streamflow had disappeared. On a watershed at Coweeta with a much deeper soil, 20 years was required to achieve a similar reduction after clearcutting (Lull and Reinhart 1967).

In snow regimes, the duration of reductions of evapotranspiration following timber harvest depends on the aerodynamic placement of snow in relation to the opportunity for soil moisture storage (Anderson 1970a, Hoover 1973).

In upland forests, three measurements may enable estimation of actual evapotranspiration and indicate the possiblity of increasing streamflow by forest cutting: soil-water measurements at the beginning of the growing season when the soil is wet and at the end of the season when it is dry, plus a record of summer rainfall. (In areas where overland flow occurs or where the soil may be fully recharged by summer rains, estimating is more complicated.) In Utah, for instance, measurements of summer losses of soil water showed that mature aspen stands used 0.5 to 4.5 inches more water from the upper 6 feet of soil than first-year sprouts of cut aspens (Tew 1967). These differences diminished rapidly in succeeding years as sprout stands matured. Mature Gambel oak utilized 1/4 to 1 inch more soil moisture than 1-year-old sprouts. (Tew 1969). Clearcutting oak and aspen can prolong savings only if subsequent sprouting is prevented. Interclonal root connections also may reduce the effectiveness of small cleared areas of aspen (Tew and others 1969). Clearcutting of lodgepole pine in the Uinta Mountains of Utah resulted in 4 inches more water left in the soil at the end of summer as compared with uncut stands (Johnston 1975).

In California, fall soil-water deficits ranging from 3 to 17 inches on natural forest sites may be reduced to 1 to 8½ inches after logging or brush removal (Anderson 1969).

Soil-water and supplemental measurements in a red fir forest in California suggest water losses of 24 inches on unlogged forest, and first-year losses of 12, 15, and 18 inches for strip, block, and selection cuts, respectively, or savings of 12, 9, and 6 inches (Anderson 1969).

Thinning can reduce use of soil water by 1 to 3 inches. In Oregon, thinned stands of ponderosa pine saplings used 1 to 2 inches less water during the growing season than untreated stands (Barrett and Youngberg 1965). Helvey (1975) found that heavy thinning of 70-year old ponderosa pine in central Oregon reduced summer soil moisture depletion by from 2.4 to 4.5 inches, but only during the first three years after treatment.

In the fall of three successive years, a Minnesota red pine stand, thinned to 60 square feet of basal area, had 1.8, 0.5, and 3.2 inches more soil water than an unthinned stand with 140 square feet (Bay and Boelter 1963). These studies indicate that forests use less soil water after cutting than before, so more water is available for streamflow. However, these are index values only. Hydrologic processes are too complicated to permit translation of differences in soil moisture and other separate processes directly into increases in streamflow.

Quantity of Streamflow

Increases in streamflow after various intensities of cutting have been demonstrated in many parts of the country (*table 8*). Treatments other than timber cutting are also shown in the table for comparison. Considering first-year increases only, the heavier the cut, the greater the increase in flow. Thus, maximum first-year increases in streamflow following clearcutting, partial clearcutting, and selection cutting are about 18, 8, and 4 inches, respectively. Where average annual precipitation is 48 to 90 inches, first-year increases following clearcutting ranged from 5 to 18 inches; with 21 to 28 inches precipitation, increases were 1 to 3 inches; where precipitation was 19 inches, no increase was reported.

In Arizona removing mixed conifer forest vegetation has increased water yields approximately in proportion to the percent of the area in cleared openings and in proportion to the amount of precipitation during a year (Rich and Thompson 1974). "Removal of moist-site forest vegetation—Douglas-fir and white fir—from 80 acres of a 248-acre watershed increased water yields 45 percent. Clearing an additional 100 acres of dry-site forest vegetation—dominantly ponderosa pine—further increased water yields. Compared to original conditions, increases varied from 81 percent at 1-inch yield from the control watershed to 109 percent at 7-inch yield from the control. Clearcutting 83 percent of a 318-acre watershed resulted in water yield increases varying from 81 percent at 1-inch yield from the control watershed to 140 percent at 7 inches from the control. Clearcutting one-sixth of a 900-acre watershed, where the remaining five-sixths of the watershed was placed in the best growing condition possible, increased water yield about 29 percent. In contrast, annual water yields following the individual tree selection harvest on South Fork of Workman Creek were not significantly changed by the treatment. A riparian cut of alder and big-tooth maple adjacent to streams and seeps that removed 0.6 percent of the total basal area of all trees on the 248-acre watershed did not significantly increase water yields."

Baker (1975) reported that winter streamflow from ponderosa pine forest areas in Arizona was increased most by completely clearing a watershed. All residual slash was piled in windrows, which were oriented to trap and shade snow. Increase in runoff has averaged 1.8 inches per year, a 33 percent increase over an 8-year period. The second largest response resulted from the removal of 75 percent of the timber basal area by thinning. Here also, the residual slash was piled into windrows. The average increase in runoff was 1.3 inches per year, or 19 percent for a 5-year period. Another watershed was treated by removing 32 percent of its timber in uniform, downslope strips. This treatment yielded a 1.0-inch per year increase in runoff, or a 16 percent increase over a 6-year period. Streamflow varied directly with amount of winter precipitation, but was reduced in amount proportional to both the insolation received (south versus north slopes) and the residual timber volume after cutting (H. E. Brown and others 1974).

Duration of Increased Streamflow—This depends on the magnitude of the initial increase, the type and intensity of cut, and the rapidity of regrowth. In the southeast, at Coweeta, after a clearcutting that increased flow 14 inches the first year, regrowth dropped the increase to 8 inches the 5th year, to 6 inches the 10th year, and to an estimated 1 inch at year 35 (Kovner 1957). A recutting of this watershed duplicated the 14-inch increase the first year, but the rate of increase dropped much faster, reaching 4 inches after only 5 years.[9] In the northeast, after 10 years there was only an estimated 0.5-inch increase on the Fernow watershed, where the first-year increase had been 5.1 inches (Lull and Reinhart 1967), and the 2.5-inch increase from a selection cutting was reduced to a negligible quantity in 3 years. Selection cuttings and thinnings have only transient influences on water yield because roots and canopies rapidly extend into occupied spaces.

In contrast, effects of treatment may persist longer in those western forests where regrowth is slow and increased streamflow is derived largely from differential snow accumulation. For example, 2- to 4-inch increases in flow after a 39-percent strip cutting of lodgepole pine in Colorado have persisted for 17 years and promise to persist considerably longer (Leaf 1975b). In an earlier study the ratio of increase in snow storage in cut plots to that in uncut plots remained virtually unchanged over a 24-year period (Hoover and Leaf 1967).

Minimum Selection Cuts—The minimum selection cut that will produce a significant increase of water yield in humid regions has been estimated at 20 percent of the basal area of a well stocked stand (Douglass 1967). Clearcutting 20 percent of a watershed would also increase water yield significantly. Annual cutting of smaller portions, as is done in sustained yield programs, may or may not increase water yield detectably. Berndt and Swank (1970) noted a significant increase in streamflow from a small forested basin in central Oregon following increased timber cutting. The criteria of "significance" are, of course, strictly from a statistical point of view. Once a physical increase is shown, statistical significance is not necessary criterion—if a 20-percent clearcut increases streamflow by a "significant" 2 inches, a 10-percent clearcut's 1-inch increase is equally as physically significant.

The greatest percentage increases (*table 8*) were registered in western studies, where runoff was normally low. The comparatively small increases resulting from cutting riparian areas are partly due to the small proportion of the total watershed that was treated.

The effects of different kinds of cutting on any one watershed, in connection with multiple-use programs, have received little study. A 356-acre demonstration pilot watershed developed at Coweeta includes programs for timber harvest, water yield, and recreational use. Clearcutting (for regeneration) 180 acres of poor oak-hickory stands, plus improvement and understory cuts in

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[9] Unpublished report, Southeast. Forest Exp. Stn., Asheville, North Carolina.

Table 8–*Increases in water yield following forest cutting, by forest type, geographic location, and type of cutting*

Forest area (acres)	Mean precipitation	Mean annual streamflow	Treatment	Percent of area or basal area (b) removed	Regrowth	Water yield increases by years after treatment									
						1	2	3	4	5	1	2	3	4	5
	— Inches —					*Inches*					*Percent*				
				(1) Mixed Hardwoods, Western North Carolina											
40	72	31	Clearcut	100	Yes	14.4	10.9	10.9	9.8	7.9	66	46	29	26	31
33	75	30	Clearcut	100	No	16.8	13.0	11.7	11.4	11.2	65	–	–	–	–
23	71	24	Clearcut	100	No	5.0	3.7	2.3	4.4	3.1	–	–	–	–	–
85	81	50	Clearcut	50	Yes	7.8	6.1	5.1	4.4	3.9	–	–	–	–	–
70	79	48	Selection cut	22b	Yes	3.9	2.2	2.8	1.1	1.5	6	5	5	3	3
212	73	42	Selection cut	30b	Yes	Averaged 0.98 per year									
71	80	51	Selection cut	35b	Yes	Averaged 2.17 per year									
50	77	41	Selection cut	27b	Yes	Nonsignificant									
22	72	33	Riparian cut	12	Yes	Nonsignificant									
				(2) Northern Hardwoods, Central New Hampshire											
39	48	35	Cleared	100	No	13.5	10.8	9.4			40	29	19		
				(3) Mixed Hardwoods, Northern West Virginia											
59	57	30	Cleared	100	No	10.3					–				
85	60	23	Clearcut (except for culls)	100 (83b)	Yes	5.1	3.4	3.5	0.6	2.2	19	16	–	–	–
59	57	30	Clearcut	50	No	6.1	5.8				–	–			
38	59	26	Selection cut	36	Yes	2.5	1.4	0.3	1.2	-0.2	10	5	1	4	–
90	58	30	Selection cut	22	Yes	0.7	0.1	-0.7	-1.6	0.7	2	0	–	–	–
85	59	25	Selection cut	14	Yes	0.3	1.3	0.3	0.3	0.0	1	5	1	1	0
				(4) Oak Type, Central Pennsylvania											
106	37	13	Clearcut	20	No	2.7					17				
				(5) Douglas-fir, Western Oregon											
237	90	57	Clearcut	100	Yes	18.2	18.0				36	33			
250	90	57	Clearcut	30	Yes	5.9	6.4	5.9	11.7	8.9	16	14	19	38	24
				(6) Aspen and Conifers, Colorado											
200	21	6.1	Clearcut	100	Yes	1.4	1.9	1.0	0.8	0.5	19	27	16	12	12
				(7) Lodgepole Pine and Spruce-Fir, Colorado											
714	30	11	Clearcut	40	Yes	3.3	5.2	3.7	4.6	5.4	32	35	43	63	71
				(8) Mixed Conifers, Arizona											
1,163	27	3.2	Clearcut	16	Yes	1.2					16				
248	32	3.4	Selection cut	32	Yes	0.5	2.0	1.6	1.9	1.2	56	45	–	–	–
318	32	3.4	Selection cut	45	Yes	Nonsignificant									
				(9) Utah Juniper, Central Arizona											
323	19	0.9	Cabled, burned, seeded to grass	100	Yes	Nonsignificant									

Table 8--*Increases in water yield following forest cutting, by forest type, geographic location, and type of cutting*

Forest area (acres)	Mean precipitation	Mean annual streamflow	Treatment	Percent of area or basal area (b) removed	Regrowth	Water yield increases by years after treatment									
						1	2	3	4	5	1	2	3	4	5
	— Inches —					*Inches*					*Percent*				
				(10) Chaparral, Central Arizona											
95	26	2.2	Herbicide	90	Yes	3.4	3.0	2.6	9.8	14.2	111	292	589	451	235
46	26	2.2	Herbicide	40	Yes (grass)	3.0	0.9	1.8			299	517	223		
				(11) Oak-Woodland, Central California											
12	25	4.1	Chemical kill	100	Yes (grass)	4.0	7.9	4.0			25	65	300		
				(12) Chaparral with Woodland along Streams, Southern California											
875	26	2.5	Riparian cut	2–4	Yes	0.4					–				

(13) Ponderosa pine, Beaver Creek, Arizona

Watershed no. and year treated	Mean winter streamflow	Treatment	Percent of area treated or basal area (b) removed	Difference between predicted and actual streamflow by years after treatment						Mean difference	
				1	2	3	4	5	6		
	Inches									*Inches*	*Percent*
12, 1967	6.04	Clearcut	100	3.79	0.92	1.81	1.47	1.39	3.29	2.00	35
9, 1968	6.70	Clearcut in uniform strips	32	1.98	.61	.34	.84	1.74		1.10	16
17, 1969	7.63	Thinning	75	.85	1.45	1.51	2.93			1.68	222
14, 1970	4.71	Clearcut in irregular strips, thinning bet. strips	50	.71	.70	1.61				1.01	21
16, 1972	5.45	As above	65	5.60						5.60	103

[1] Blank = no data available; dash = no percent given in source reference.

Compiled as follows:

(1) Dunford and Fletcher 1947, Johnson and Kovner, 1954, Hewlett and Hibbert 1961, Hibbert 1967
(2) Hornbeck and others 1970, Pierce and others 1970
(3) Reinhart and Trimble 1962, Reinhart and others 1963, Patric and Reinhart 1971, files of Northeastern Forest Exp. Stn.
(4) Lynch and Sopper 1970
(5) Rothacher 1970
(6) Bates and Henry 1928, Reinhart and others 1963
(7) Goodell 1958, Martinelli 1964
(8) Rich 1968, U.S. Dep. Agric. Forest Serv. 1964a
(9) Brown 1965
(10) Hibbert 1971
(11) Lewis 1968
(12) Rowe 1963
(13) H. E. Brown and others 1974

92 acres of a cove type to increase water yield, increased streamflow the first year by 10 percent (6.2 inches) (Hewlett and Douglass 1968).

Streamflow Timing—The time of the year when streamflow increases following timber harvest has been less dealt with experimentally than total annual increases, for they have an added dimension of variability and hence are more difficult to demonstrate to be statistically significant. Examples of timing of streamflow must suffice.

At Fernow, clearcutting two watersheds in hardwood forest increased the low flow in June through October by about 1/2 to 1 inch per month (Kochenderfer and Aubertin 1975). Flow from November through May was less than or about equal to flow from the uncut watershed. Before the cutting, streamflow had dried up periodically; after treatment, flow remained above 0.3 csm (Patric and Reinhart 1971).

At Coweeta, increases in streamflow during the 7 years when one watershed was kept clearcut started to increase (compared with the control) in June, with a 0.2-inch increase, reached about 1-inch increases in the months of August through October, and increased in November and December to 1.5 inches per month; then the increases were less, until no appreciable increases were noted during April and May. Increases during the 4 driest months, August through November, totalled 4.42 inches, double the normal flow and equivalent to about one-half of the total average annual increase from the clearcutting of 8.67 inches (Douglass and Swank 1975).

At Fraser, Colorado, nearly all of the increased flow of 3.5 inches, associated with the 39-percent strip cutting, came in May and early June, with some deficit in flow in late June, about equal to the excess in early June. Recession flows during the July through September period were about equal in the cut and the control watersheds (Leaf 1975b).

At the Central Sierra Snow Laboratory, a commercial selection cut increased streamflow by 7 inches; about half of that increase was in June (Anderson 1963).

At the H. J. Andrews Experimental Forest, 80 percent of the 18-inch increase in streamflow resulting from a clearcut harvest occurred in the wet October to March season, but even in the driest month, September 1967, the increase was 0.15 inch, a 150-percent increase over that from the uncut condition. This increase is important, for it supplies an extra 87,000 gallons per day per square mile of clearcut watershed. Three-month increases averaged 0.8 inch in July to September and 3.6 inches in April through June (Rothacher 1970).

In all areas the streamflow following forest harvesting increased in seasons when augmented water supply was most needed.

Peak Flows and Stormflow Volumes

Peak flows result from the simultaneous arrival of water and waterborne debris from many sources. The effect of timber cutting on small watersheds indicates its effect on floods in general. The first eastern study of effects of clearcutting on watersheds was started in 1941 at Coweeta Hydrologic Laboratory. A 33-acre watershed was clearcut; trees were left where they fell, and sprouts were cut annually. Annual streamflow increased by an average of about 11 inches, but maximum peak discharges did not increase (Hoover 1945, Hewlett and Hibbert 1961).

More recently at Coweeta, after a 108-acre mature hardwood forest on a high-elevation watershed was clearcut, peak flows increased by an average of 9 percent. Volume of stormflow from all major storms increased by an average of 11 percent, or 0.23 inch at the mean storm runoff of 2.1 inches. Larger storms produced greater effects: a 7-day flood sequence increased the volume of storm runoff by 22 percent but amounted to less than 1 inch of direct runoff. No overland flow was observed (Hewlett and Helvey 1970).

A study of commercial logging on watersheds in West Virginia showed that the effects on storm peaks depended on the season (Reinhart and others 1963). In this study all timber of commercial value (86 percent of the total volume) was removed from a hardwood-forested watershed. Instantaneous peaks (all far less than flood magnitude) during the growing season increased by an average of 21 percent; in the dormant season they were apparently reduced by 4 percent. In a clearcut watershed storm-period discharges were more than doubled in the growing season, and snowmelt flows were reduced. In Japan, clearcutting a 6-acre watershed increased peak runoff from heavy rains about 20 percent (Maruyama and Inose 1952). No overland flow was observed in either of these studies. The Japanese, Fernow, and Coweeta studies indicate that timber can be cut heavily without causing watershed deterioration that results in overland flow, although some peak flows increase.

In a study at the Hubbard Brook Experimental Forest in New Hampshire, an unusual treatment —removal of both forest and ground cover and prevention of regrowth—was applied. Summer peak flows increased considerably. For the six highest peak flows during June through September, 1966 through 1969, in the untreated control watershed, the peaks for a 39-acre denuded watershed averaged double the expected 49 $ft^3/s/mi^2$, with the increases for the individual events ranging from -19 to 250 percent. Most of this variation was due to differences in available storage for soil water; infiltration, apparently, was not a limiting factor. Changes in dormant season high flows not involving snowmelt were usually negligible; this indicated the similarity in soil water regimens of the treated and untreated watersheds in this season (Pierce and others 1970, Hornbeck 1973).

Clearcutting can either decrease or increase rates of flow when snowmelt is involved. Clearcutting a small watershed at Hubbard Brook increased peak flows early in the snowmelt season by as much as 35 percent (from 59 to 79 $ft^3/s/mi^2$) and decreased them as much as 66 percent (from 34 to 12 $ft^3/s/mi^2$) later in the season (Hornbeck and Pierce 1969).

Western situations are complex, and research results reflect this. First, fewer data are available from western experimental watersheds (excluding the Southwestern brushland region); moreover, for much of the region the source of floods is rain on snow or snowmelt rather than rainfall alone. At the H.J. Andrews Experimental Forest in central Oregon, along the western slope of the Cascades, no effect of clearcutting one-third of a 250-acre watershed was at first apparent on maximum flows because rainfall came mostly in low-intensity winter storms of considerable duration (Rothacher 1965a). A later report (Rothacher 1971) presents data showing that increases in storm peak flows in the clearcut watershed depended on the amount of rainfall during the 30 days before the storm. In the 1965-69 period, the peaks for 84 percent of the storms were greater in the clearcut watershed than in the uncut control, and were generally greater when the rainfall in the preceding 30 days had been less than 22 inches. Ninety percent of the 73 storms in the 1965-69 period occurred when antecedent rainfall had been less than 22 inches, but the highest peaks generally occurred when antecedent conditions had been wet. Peaks showed little or no increase after 22 inches or more of antecedent rainfall. The record shows the damping influence of the forest on peak flows from storms. Other clearcuttings in Oregon (Krygier and Harr 1972) increased peaks from fall storms by 90 percent and from winter storms by 28 percent.

At Fraser, Colorado, harvesting gave mixed results: cutting 39 percent of a lodgpole pine-spruce-fir stand in strips 1,2,3, and 6 chains wide increased peak discharge from snowmelt by 50 percent the first year; discharge the next year was 23 percent less than had been expected, and the third year it was 45 percent greater than had been predicted (Goodell 1958). For this high Rocky Mountain area, maximum peaks are less than 22 $ft^3/s/mi^2$.

Lesser cuts have lesser effects. At Coweeta, cutting a dense laurel-rhododendron understory and riparian (streamside) vegetation did not increase maximum peak discharges; and there were no overland flows (Johnson and Kovner 1954). At the Fernow, selection cuts that removed 20 to 59 percent of the original stand produced no perceptible effect on peak flows (Reinhart and others 1963).

Studies of the effects that various treatments have on small watersheds under varied conditions hardly ever tested the effects of rare events associated with large floods—large areas of frozen soil, snowmelt augmenting rain runoff, or large floods carrying debris. Furthermore the treatments usually applied do not drastically change the soils. Reinhart (1964b) pointed out that distinction should be made betweeen clearcutting steep lands and converting them to pasture or crops, and clearcutting gentle slopes without seriously compacting the soil and permitting regrowth. As long as the forest floor remains intact, most of the beneficial hydrologic effects of the forest may continue to be present.

Peak flows for several whole large watersheds in Oregon were considerably changed (Anderson 1952). Where watersheds had been logged and then burned and where 45 percent of the area was left unstocked or poorly stocked, peak flows increased by more than 30 percent.

Anderson and Hobba's (1959) analysis of forest cutting and peak flows on 54 watersheds in the Northwest approached the forest-flood relationship broadly. From data on watershed differing in size, geology, topography, and land use, they developed equations for predicting peak discharges based on climatic and watershed variables; they then related deviations of predicted from actual discharges to difference in forest age and stocking. In those watersheds the standard cutting practice had been to clearcut large blocks and then broadcast-burn the slash. Anderson and Hobba predicted that clearcutting 1 square mile of Douglas-fir under the practice then current would increase the flood peak of rainstorms on ripe snow from a watershed by 103 ft^3/s.

The results of their analysis indicate that forest cutting does not drastically affect major floods from large basins if sustained-yield management is *properly applied* and if the logged area is promptly and fully restocked. If, for instance, 1 percent of a watershed were cut over each year, the increase in peaks would average about 9 $ft^3/s/mi^2$. This would be only a 6 percent increase in the 100-year flood, but more than 20-percent increase in the mean annual flood. On the other hand, large areas in the region studied have failed to restock after fire or logging. Further, some watershed channels might be unstable under a 20-percent increase in annual flood flow.

An analysis of snowmelt floods on watersheds on the east side of the Cascade Mountains showed that peak flows would be expected to increase by about 11 percent when one-half of a watershed was burned or poorly stocked; but logging or burning half of the watershed would be an extreme case (Anderson and Hobba 1959).

Water Temperature

Clearcutting near streams sometimes raises the water temperature sufficiently to reduce fish populations. One obvious remedy is to leave trees or shrubs along the channels, where they will shade streamflow (Brown and Krygier 1967). In West Virginia, Reinhart and others (1963) found that clearcutting raised maximum temperatures by an average of 8°F during the growing season. Temperatures exceeded 75°F several times; these temperatures would probably harm most resident trout and salmon (Lantz 1971a). In western Oregon, daily temperatures rose 2° in March and as much as 14° in September; from August 1 to 15 the mean high temperature was above 70°F. On the H.J. Andrews Experimental Forest one clear day in May, the midday temperature of water flowing for 1 hour through an exposed channel 1,300 feet long increased by 16°F (Brown and Krygier 1967).

Widespread checks of similar logged and unlogged drainages in Oregon have shown temperatures to be as much as 10° higher in logged areas where riparian vegetation was completely removed (Chapman 1962). Two years after complete clearing of a Douglas-fir forest in the Alsea Watershed, the stream temperature reached a high of 85°F—28° higher than on the unlogged control (Krygier and others 1971). On a patch-cut watershed with a buffer strip along the main stream, the maximum temperature was 61.5°F.

Exposure of the stream surface to direct solar radiation is the principal cause of increased water temperature (Brown and Krygier 1967). Understory vegetation that survives clearcutting may provide considerable protection. For example, at the H.J. Andrews Experimental Forest, clearcutting along increased maximum water temperature 4°F, but the slash burning that followed removed old protective stream cover; then the mean monthly maximum water temperature for June, July, and August increased by 12° to 14°F (Levno and Rothacher 1969).

Water temperature may be lowered as a stream flows from an exposed area into a protected one. For instance, routing an open, exposed trout stream in Wisconsin through the shade of a willow grove reduced later afternoon summer water temperatures by 10° to 11° F (Stoeckeler and Voskuil 1960). In one study of a patch-cut logging area in Oregon, water from the logged portion cooled as it passed through shaded areas downstream or was diluted by cooler water from uncut watersheds (Levno and Rothacher 1969). However, in a large-scale test in the Umpqua Basin, also in Oregon, local shading of the stream apparently did not significantly lower the temperature of water that had been warmed by exposure in a logged-over area upstream; the investigators concluded that the chief cooling effects were from inflow of groundwater (Brown and others 1971). Shading upstream tributary streams is important.

Certain forest effects on radiation and subsurface flow account for significant differences observed between large streams and small ones. On reaches of large streams that are oriented east and west, for example, longwave radiation from trees on the north side may well heat the water in summer, when the sun is high. Removing these trees would both reduce this heating and release cooling groundwater in summer; (it might possibly increase warming groundwater flow in winter). Clearly, tree cutting alongside streams should not be prohibited on the basis of stream shading alone. The degree of shade desired may depend on the effects of the resultant stream temperature on water chemistry.

Water Chemistry

Timber felling and repeated herbicide treatment completely denuded a forest ecosystem on a New Hampshire watershed that had podzol soils derived from glacial tills. This treatment increased cation loss by 3 to 20 times; nitrate concentration in the streamwater increased from about 1p/m to 58 p/m (Bormann and others 1968). As this study continued, nitrate concentrations of as much as 80 p/m were noted, with an overall increase of about fiftyfold for the 3-year period 1967 through 1969 (Pierce and others 1970). This nitrate concentration produced a noticeable algal growth in the stream. Later, Pierce and others (1972) reported on the effect of timber harvesting, also in New Hampshire. From one clearcut area, the highest nutrient concentrations were only one-third to one-half the levels reached in the denuded watershed. "For the first 4 years of the strip-cut harvest, stream water concentrations increased by more than 7 mg/l for nitrate, 0.9 mg/l for calcium, and 0.3 mg/l for potassium. Sulfate concentrations declined by as much as 1.5 mg/l. In contrast, block clearcutting caused maximum increases of 23 mg/l for nitrate, 3 mg/l for calcium, and 1 mg/l for potassium, and an apparent decrease of 2 mg/l for sulfate." (Hornbeck and others 1975).

Other studies have shown lesser effects of watershed disturbance on nutrient discharges in streamflow. Aubertin and Patric (1974) found only a slight increase in dissolved solids during the 2 years following the clearcutting of a hardwood forest watershed in West Virginia; the maximum concentration of nitrate-nitrogen measured was 1.4 p/m.

From their studies of mineral balances for various disturbed and undisturbed watersheds, Swank and Elwood (1971) concluded that the rather drastic alterations of the forest ecosystem at Coweeta Hydrologic Laboratory had apparently not resulted in large, accelerated cation losses to drainage waters. However, they did not measure mineral presence on watersheds immediately after tree cutting or other disturbances. They reported that 10 years after a commercial logging, nitrate-nitrogen in streamflow increased by 1.9 pounds per acre per year. This is less than the 3 pounds normally added from rainfall (Swank and Douglass 1975). While forests were in various stages of natural revegetation following cutting, increased nitrate-nitrogen content in the streamflow was evident for at least 10 years after cutting, but appeared to return to "baseline levels" 20 years after the cutting. In a study in Minnesota, Verry (1972) reported no change in the composition of streamwater after clearcutting of aspen.

Fredriksen (1971) measured the loss of nutrients after timber harvesting and broadcast slash burning in old-growth Douglas-fir on the H.J. Andrews Experimental Forest. Nutrient cation discharge was 1.6 to 3.0 times that from an undisturbed watershed; annual nitrogen loss averaged 4.6 pounds per acre compared to 0.16 pound per acre from the undisturbed watershed; but average monthly concentrations never exceeded 0.4 p/m.

Hart and DeByle (1975) studied subsurface water chemistry under different slash treatments after clearcutting of a stand of 175-year old lodgepole pine. Except for a flush of nutrients soon after slash burning, they found no apparent differences in the soil solution under four slash disposal systems.

Brown's review (1972) of logging and water quality concluded that nutrient losses from Northwest forests after clearcutting were a minor short-term problem for both the terrestrial and aquatic systems. Gibbons and Salo (1973) have published an annotated bibliography of 278 publications related to the effects of logging on fish populations in the Western United States and Canada.

Summary

Timber harvesting increases water yield primarily by reducing evapotranspiration. The potential for increased yield is greater where precipitation is higher. Where rainfall and seasonal evapotranspiration are important, the situation is different from those involving snowfall and changes in snow interception, distribution, and melt rate.

In areas where snow is not important, the increase in water yield the first year after cutting appears to be proportional to the percentage of basal area cut, and the water yield increases mainly during and immediately after the growing season. Increases diminish as the forest regrows; they may continue for 10 years or less where regrowth is rapid and soils relatively shallow. Where regrowth is slow or where soils are deep, increases may persist much longer.

Water yield increases from timber harvesting in snowpack areas occurs mostly in the spring or early summer period of snowmelt discharge; the increases following harvesting persist longest where vegetation recovery is slow.

The effect of timber harvesting on floods varies. Several factors limit increases in flood peaks and flood runoff even after clearcutting, the harvest method with the greatest impact. Timber harvesting does not generate overland flow except where it disturbs the forest floor. Overland flow from logging roads and other disturbed areas is partly absorbed by infiltration into adjacent areas, especially where logging operations are well planned and executed. The effect of cutting on flows is diminished, especially in regions where precipitation is ample and well-distributed, as regrowth reestablishes interception and soil-water retention opportunity. Under sustained-yield management or where forest holdings are many and small, only a small proportion of any sizable drainage is likely to be cut over at one time.

The fact remains that clearcutting can increase flood flows, especially when soil disturbance is widespread, where regrowth is slow or covers only part of the area, or when snowmelt contributes a sizable portion.

Several conditions accentuate the problem in the West as compared to the East: These include slow regrowth in many areas because of low rainfall, especially in the growing season; greater volumes of timber and bigger logs in other areas, resulting in the need for bigger equipment and greater soil disturbance; and the practice in many areas of burning debris after logging.

Timber harvesting and its associated roads can, have, and often still do cause serious erosion and sedimentation. The amount of damage on site, in local streams and downstream, varies widely with topography, climate, soils, and the amount of soil disturbance, which depends on such things as care in logging, intensity of cut, and the equipment used. For many areas, responsible logging can keep damages within bounds, but better practices than those applied in many areas in the past will be required.

In some steep, fragile areas, conventional logging may not be possible without intolerable damage. Use of the skyline crane, or of balloon or helicopter logging (assuming their use is demonstrated to be practicable) may make timber harvesting feasible in these areas. Even with such techniques the susceptibility of stream banks to scour and sliding induced by increased streamflow following timber harvesting will need to be appraised.

For many of the same reasons we discussed with respect to timber harvesting and floods, the effect of timber harvesting on erosion, including its effect on water quality, is generally a greater problem in much of the West than it is in the East.

Timber harvesting sometimes increases stream water temperatures to the detriment of cold-water fish. Stream temperatures can be kept cool by preserving all or part of the vegetation shading the stream channel. Increased water temperatures may sometimes stimulate a favorable production in the food chain.

Research to date indicates that clearcutting does not increase volumes of dissolved solids enough to lower water quality below drinking water standards. However, nitrogen discharge may frequently, though temporarily, exceed the concentrations necessary to increase the growth of algae. It has been reported that less than 0.5 p/m of nitrogen may cause such growth (Tarrant 1972). Of the studies so far conducted, only those on podzol soils in New Hampshire indicate that clearcutting may diminish the nutrient capital of the soil. Partial cuts, of course, have less effect. Further research on this problem is needed and is in progress at most forest experiment stations and at several universities.

Regeneration and Tree Planting

Forest regeneration and subsequent growth increase interception and, particularly, transpiration. Whether regeneration increases infiltration capacity depends on the soil's initial capacity. Water yield, peak flow, erosion, and sedimentation will gradually be reduced as trees grow in height and density.

Interception

The growth of conifer plantations over a period of years may substantially reduce water yield by increasing interception (Swank and Douglass 1974). Take, for example, an annual rainfall of 41 inches consisting of ten 1-inch storms, thirty 0.5-inch, and eighty 0.2-inch. According to Helvey's (1967) equations, a 10-year-old eastern white pine stand would intercept 8.3 inches of water, a 35-year-old stand would intercept 9.9 inches, and a 60-year-old stand would intercept 13.1 inches—a reduction of water available for annual streamflow amounting to 4.8 inches at the end of a 60-year period. The oldest pine stand intercepts twice as much as the youngest, and twice as much as mature hardwood stands. From a single flood-producing 2-inch storm, for example, a 10-year-old white pine stand could intercept about 0.17 inch, a 35-year-old stand, 0.23, and a 60-year-old stand, 0.34 inch (Helvey 1967).

Infiltration, Overland Flow, Erosion, and Sedimentation

Increased rates of infiltration and diminished overland flow make more water available for evapotranspiration so less for streamflow. This change normally reduces both water yield and storm discharges. In the East, this effect is most pronounced in the growing season, when streamflow is much less than in the cooler months.

Infiltration, overland flow, and , to some extent, surface detention change as a plantation matures. The significance of the change depends on the surface cover and infiltration capacity at the time of planting. Planting a bare, eroding site may increase infiltration in 10 years to the point where overland flow and erosion practically cease (Ursic and Dendy 1965). On the other hand, mechanical site preparation in some areas of the South is reported to cause severely accelerated erosion (Dissmeyer 1976).

Old fields may support enough invading vegetation to stabilize soil without trees. In West Virginia, measurements of streamwater quality showed that farmlands, abandoned for two decades, have healed naturally so the areas produce only slightly higher turbidities than undisturbed forest land (Hornbeck and Troendle 1969).

In Tennessee, planting about one-third of the severely eroded 1,715-acre White Hollow watershed, mostly to pine, and permitting natural regrowth on the rest of the watershed reduced the sediment load following the average storm from 7.3 tons in 1935-36 to 0.3 ton in 1954-55, a reduction of 96 percent. The reduction each year averaged about 15 percent of the previous year's sediment load (Tennessee Valley Authority 1961). Planting two-thirds of the Pine Tree Branch watershed in Tennessee reduced the sediment load from 24.3 tons per acre in 1942-45 to 7.6 in 1946-50, to 2.2 in 1951-55, and to 1.1 in 1956-60, an overall reduction of 95 percent (Tennessee Valley Authority 1962). In both of these watersheds, installation of check dams and other erosion-control measures was responsible for an undetermined portion of the improvement.

Planting loblolly pine in northern Mississippi sharply reduced sedimentation. Annual rates of erosion loss on four different types of planting sites were:

Land Use:	Mean *Tons/Acre*	Range *Tons/Acre*
Pine plantation (22 yrs old)	0.02	0.00 to 0.08
Mature pine and hardwoods	0.02	0.01 to 0.04
Abandoned fields	0.13	0.01 to 0.54
Cultivated lands	21.75	3.28 to 43.06

The pines had been planted on abandoned fields where erosion had removed an estimated 2 feet of the surface and had cut gullies 5 feet below the level of the remaining soil (Ursic and Dendy 1965). The planting has reduced erosion to near the geologic norm for forests in the area.

Six years after trees were planted on eroded cropland at Coshocton, Ohio, they established a nearly complete ground cover, sheet erosion practically ceased, and small gullies were stabilized (Harrold 1961).

Soil-Water Storage

Major increases in detention storage may also follow forest establishment and growth. For instance, on an experimental watershed at Coshocton, Ohio, the volume of noncapillary pore space in the surface 7 inches of three types of soil under three kinds of cover was as follows (Harrold and others 1962):

	Idle land	Pine cover	Hardwood cover
	Percent (by volume)		
Soil type:			
Keene silt loam	11.4	14.7	16.5
Muskingum silt loam over:			
Sandstone and shale	14.9	23.4	23.1
Sandstone	21.3	25.2	24.4

Thus the two forest stands had from 15 to 55 percent more detention storage space than the idle land.

Reforestation of old fields, however, may not quickly restore detention storage everywhere. In South Carolina's Piedmont, Hoover (1950) found detention storage of 4 inches in the upper 24 inches of undisturbed hardwood forest soil, whereas under a pine stand 25 to 30 years old with a sandy plow horizon, detention storage was 1.2 inches; detention storage totaled 17 and 5 percent by volume, respectively.

Evapotranspiration and Streamflow

Evapotranspiration increases as regeneration develops. After two clearcut watersheds at Coweeta were planted to white pine, streamflow steadily decreased (and evapotranspiration — including evaporation of intercepted water — increased). The cleared plantations averaged 2.5 and 9 inches more water yield, respectively, the first 6 years after planting; but once the crown began to close the rate of increase declined to 1 to 2 inches per year, until at age 10 years the first watershed had 3.7 inches less yield, and at the age of 11 years the second had 1.3 inches less (Swank and Miner 1968). At age 15 years both watersheds had about 7.9 inches less streamflow than had been predicted if the watersheds had remained in hardwoods (Swank and Douglass 1974).

Streamflow from a 491-square-mile watershed in the Adirondacks decreased 7.7 inches (or evapotranspiration increased) over a period of 39 years, as the forest density and crown cover of conifers increased (Eschner and Satterlund 1966).

The amount of reduction in yield must obviously depend on the proportion of the watershed planted. If we extrapolate the decreases in water yield [*table 9*] for partial plantings in Ohio, western Tennessee, and New York to those for complete planting, the reduction would range from about 6 to 9 inches for four of the five examples, and to 19 inches for the New York watershed where 35 percent of the area was planted. The decrease in New York may have been greatest because snow was an important meteorological factor there.

Peak Flows

Increases in interception, infiltration, and opportunity for soil-water storage concurrent with plantation growth may sharply reduce peak discharges. This reduction varies with the type of cover before conversion, and the proportion of the watershed planted; reductions differ also between seasons of the year. The results of four studies appear in *table 10*. The reduction in peaks of 16 to 66 percent in the New York study was attributed to the lower melt rate of snow shaded by the conifers in winter; some of this reduction, however, could have resulted from greater retention of soil-moisture provided by increased transpiration during the preceding growing season.

Planting the Tennessee watersheds reduced summer peaks by amounts ranging from 62 to 92 percent. The much greater reduction in winter peaks on the Pine Tree Watershed, compared to those on White Hollow, may be due to the relatively greater area planted and to the smaller area of the watershed.

A planted forest appears to be more effective in reducing peak flows than a cutover forest is in increasing water yield. This apparent difference probably arises from the establishment of forest floor and improved soil conditions in the new plantation, whereas merely cutting the forest trees does not, by itself, usually destroy the forest floor or the hydrologic attributes of the soil. Then too, the cut forest often recovers to some form of vegetation before the soil hydrologic attributes deteriorate sufficiently to affect most flood-producing events.

Planting trees, especially conifers, effectively reduces peak flows. Planted land is likely to receive better protection from fire and grazing than idle land—protection that will maintain flood-control benefits.

Above-normal temperatures in the spring occasionally cause abnormally rapid melting of snow accumulated under plantations; and the greater the depth of snow in the forest, the more it may add to above-normal peak flows. Such flows are most damaging when they are well synchronized, which means that heavy flows from all parts of the watershed arrive downstream at the same time. Such watersheds require desynchronization of peak flows; this is provided by the juxtaposition of open and forested lands such as now exists in the northern Allegheny Plateau of New York (Satterlund and Eschner 1965); a mixture of conifer and hardwood areas may also desynchronize potentially destructive peak flows.

In forest regeneration and tree planting, site preparation may include measures that lay bare

Table 9—*Effects of reforestation on water yield from varied conversion plantings in Ohio, Tennessee, New York, and North Carolina*

Location	Forest cover before planting	Pretreatment mean annual . . .		Conversion planting by extent and type	Reduction in water yield for given year
		Precipitation	Streamflow		
		Inches			*Inches*
(1) Ohio	30% hardwoods	38	12	71%, pine	5.3 (9 yr)
(2) Western Tennessee	23% hardwoods	50	10	65%, mostly pine	3 to 6 (16 yr)
(3) Central N.Y. (3 watersheds)	1. Mixed hardwoods	38	21	47%, conifers	4.2 (24 yr)
	2. do.	41	24	58%, conifers	6.8 (23 yr)
	3. do.	41	25	58%, conifers	5.1 (23 yr)
(4) Western Tennessee	65% mixed hardwoods and pine	47	18	34%, mostly pine	0
(5) Chenango River Basin, New York	Abandoned farmland	45	25	7%, conifer plantations (10% second growth hardwoods)	1.0 (42 yr)
(6) Western North Carolina	Hardwoods:				
	Watershed 1	68	31	100%, white pine	5.6 (10 yr)
	Watershed 17	76	27	100%, white pine	10.9 (11 yr)

Compiled as follows: (1) Harrold and others 1962; (2) TVA 1962; (3) Schneider and Ayer 1961; (4) TVA 1961; (5) Muller 1966; (6) Swank and Miner 1968.

the mineral soil to improve the seedbed for natural seedfall; it could include also any methods for removal of vegetation that would compete with the trees being planted. These practices may promote erosion and sedimentation and therefore must be used with care. Wherever dense stands of brush have been removed, increased streamflow must be expected until vegetation is reestablished and develops.

Summary

Regeneration of forest stands, either by natural seeding or by planting trees after timber harvest, reverses the effect of harvesting. Water yield, stormflow, erosion, and sedimentation are likely to be reduced. The rate of this reduction depends upon the rate of growth of new herbaceous and woody vegetation, which is influenced by climate, the success of regeneration measures, and other factors.

Planting of previously unforested areas can have a much greater effect than reforestation; the difference in effects depends largely on the extent to which the prior cover protected the site and utilized available water in evapotranspiration.

Type Conversions

Conversion from one vegetation type to another may be advocated for a variety of reasons, including greater timber production or increased water yield. Conversion may have important hydrologic effects, but firm data are scarce for many of the different possible conversions.

Most tree planting in the East has been conifers, even where hardwoods were the original cover. Studies in Michigan and North Carolina showed that conifers use more water than hardwoods. In northern Michigan the annual yield of water from a jack pine plantation was 2.6 inches less, and red pine with an oak overstory 3.0 inches less than the yield from a deciduous stand (Urie 1966, 1967). At Coweeta two watersheds replanted to white pine yielded about 7.9 inches less water after 15 years than the original hardwood forest. Most of this reduction occurred during dormant seasons, but some occurred in each month (Swank and Douglass 1974). However, streamflow increased during the first 6 years by an average of 2.5 inches;

Table 10–*Effects of reforestation on peak flows from selected experimental watersheds*

Watershed location	Area	Watershed condition		Effect on peak flows
		Before treatment	After treatment	
	mi^2			
(1) Shackham Brook area Near Truxton, N.Y.	3.12	25% deciduous 1% coniferous 74% pasture and crops	27% deciduous 57% coniferous 16% pasture and crops	From 1939 to 1957 peak flows were reduced by 41% ranging from 66% in November to 16% in April.
(2) White Hollow Watershed Mason Co., Tenn.	2.68	66% poorly stocked mixed hardwood and pine 4% cultivated 4% cultivated 26% abandoned land	100% mixed hardwood and pine	From 1935-36 to 1942-49, summer peak discharges were reduced from 73% to 95%, dependent on initial soil wetness and rainfall intensity. Winter peaks were reduced from 0% to 28%, depending on amount surface runoff.
(3) Pine Tree Branch Watershed, Henderson Co., Tenn.	0.14	23% deciduous 16% cultivated 19% pasture 50% idle 2% miscellaneous	33% deciduous 65% coniferous 2% miscellaneous	From 1941-45 to 1951-60, summer peaks were reduced 92% to 97%, winter peaks 71% to 92%, depending on rainfall intensity and soil wetness.
(4) Watershed 172 Coshocton, Ohio	0.068	29% woodland 51% pasture 20% idle	43% natural woodland 57% forest plantation (pine and locust)	From 1938 to 1957, average growing season peaks were reduced by 59%; dormant season peaks were reduced by 69%. (Mean peaks were 35 and 46 $ft^3/s/mi^2$ in growing and dormant seasons, respectively.) No effect was found on peaks from extreme storm occurrences (data were insufficient for rigorous analysis).

Compiled as follows: (1) Schneider and Ayer 1961; (2) TVA 1961; (3) TVA 1962; (4) Harrold and others 1962.

so 15-year average reduction was about 1.7 inches per year. Under intensive management, including periodic thinnings, intermediate harvests, and final cutting, the water yield will be partly restored and the value of pine products may justify conifer planting, even if it causes some water loss.

Brushland has been converted to grassland range in California to increase water yield and forage production. Differences in water yield may be chiefly a matter of rooting depth, since the shallower rooting grass transpires less moisture than trees. Other possible differences in water use between grass and forest are the lower height and smoother surface of the grass, which reduce both energy absorption and vapor exchange. The shorter growing season of grass also influences its use of water. When precipitation is adequate to charge the soil mantle, the potential annual increases from conversion of chaparral to grassland range can amount to 1.2 inches for a 3-foot soil, 3 inches for a 6-foot, and 6 inches for a 9-foot soil (Bentley 1967). Rowe and Reimann (1961) showed that increases occurred only in years when rainfall exceeded 25 inches and only when deep rooted weedy herbs were not present. Root depth was the key to difference in water use between trees and grass in western Colorado. Quaking aspen used 19 inches of water, spruce 15, and grass 9 inches during the growing season. Use of moisture by grass was confined almost entirely to the upper 4 feet of the 8-foot-deep soil (Brown and Thompson 1965).

In Arizona, conversion of brush to grass increased streamflow from small watersheds by one-third so that present annual water yield is as much as 5 inches depending on soil depth and amount of precipitation (Ingebo and Hibbert 1974). In another Arizona study (Longstreth and Patten 1975), conversion from chaparral to grass increased water discharge by four times, but, except for nitrogen, ion concentrations were similar with and without conversion; nitrate reached 4 mg/liter under grass, but was rarely detectable under the deep-rooted chaparral.

Potential increases in water yield diminish as regrowth increases. Bulldozing woodland brush at high elevation in California saved 4 to 5 inches of soil moisture the first year for soils 4 feet deep; by the fifth year no saving occurred because of use by brush sprouts (Anderson 1963). A further benefit was delay in snowmelt; in the bulldozed area the melt in the April 1 - May 10 period was 3 inches less than it had been prior to brush treatment. When the forest becomes established in this area it promises 7 inches of delayed snowmelt compared with the brushfield.

Grassland converted from steep forest and brushland is a principal source of increased suspended sediment in the streams of northern California (Wallis and Anderson 1965). Conversion to grass of 15 percent of the steep forest lands was followed by a 4.7-fold increase in sediment discharge. Erosion the first year after a controlled burn in Los Padres National Forest produced 3 tons of sediment per acre from steep slopes; runoff water contained only traces of nitrogen, but 13 lbs/ac was lost in sediment (DeBano and Conrad 1976). Areas proposed for conversion to grass cover should never include steep slopes or shallow or infertile soils liable to soil erosion or slippage.

Mass slope instability under grass on steep slopes is a major problem (Rice and others 1969, Rice and Krammes 1971). On the San Dimas Experimental Forest, areas of burned brush converted to grass had 8-fold increases in landslides and sediment production (Rice and Foggin 1971). Similar consequences were noted in a northern California study.[10]. Surveys have shown that 25 to 30 percent of the chaparral area in southern California and Arizona can be classed as potentially productive for forage (U. S. Senate Sel. Comm. Natl. Water Resour. 1960b). However, these estimates were made without benefit of recent research results, either on methods of conversion or on the consequences of conversion to grass.

At Coweeta, a 22-acre forested watershed was clearcut, fertilized, limed, and seeded to grass—Kentucky 31 fescue. The first-year water yield was 0.67 inch less than the yield from the original forest. After a decline in reserves of fertilizer and in the production of dry matter, water yield increased until by the fourth and fifth years it was averaging about 5.8 inches more than yield from the original forest, an 18-percent increase. In the sixth year the area was refertilized; the grass responded vigorously, and the increase in water yield dropped to near zero (Hilmon and Douglass 1968). Thus grass may present a water-saving alternative in forest areas that have suitable soils and topography. Murai (1975) noted possible adverse results of conversion from forest cover to grass. He reported that whereas natural grassland had an infiltration capacity of 40 to 70 percent of forest land, a forested area converted to grass cover had infiltration capacity of only 20 to 25 percent of its capacity when in forest. Contemplated conversion of forest land to grass should be considered with due respect to the possible adverse hydrologic consequences.

The conversion of forest to agricultural or urban use causes major hydrologic changes, but the problems created are in agricultural and urban hydrology rather than forest hydrology, and therefore are not discussed here. However, where such conversions are being made, the hydrologic and other benefits of keeping some portion of the area in forest cover, and properly protecting and managing it, should not be overlooked.

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[10] Burgy, R. H., and Z. G. Parazifirou. 1971. Effect of vegetation management on slope stability. (Unpublished report on file, Dep. Water Sci., Univ. Calif., Davis.)

Fertilizers, Herbicides, and Insecticides

Intensive forest management may include the use of fertilizers, herbicides, and insecticides. These materials can contaminate streamflow and groundwater, but proper control of treatments can substantially reduce this threat to watershed values. The future role of chemicals in forestry has been discussed by Tarrant and others (1973). They predicted that selective, less persistent chemicals will continue to be used in forest management, but they state that chemical applications basically are treating symptoms of unhealthy ecological conditions.

Fertilizers

Fertilizing forest to increase growth has become accepted practice in some parts of the country. More forested areas have been fertilized in the Southeast and Pacific Northwest than elsewhere. In the Pacific Northwest about 300,000 acres of forest land are fertilized annually (Moore 1974). Fertilizers may be used commonly in the future, but their effect on water quality must be considered; a few studies have already been conducted.

Heikurainen and Paivanen (1970) reported the effects of forest thinning, clearcutting, and fertilizing on the hydrology of drained peatland in Finland. The groundwater table rose as much as 6 inches in summer after the heaviest cutting. Fertilizing, with associated growth stimulation, lowered the groundwater table by 2 to 3 inches, and there was an associated decrease of 24 to 28 percent in outflow. Moore (1975) fertilized a 169-acre forested watershed with 426 pounds of urea (200 pounds nitrogen) per acre and found little effect on water quality. Only one-half pound per acre was discharged in streamwater the first year; maximum concentrations found in the streamwater were 1.4 p/m of urea and less than 0.2 p/m for nitrate-nitrogen. Aubertin and others (1973) applied 500 pounds of urea (235 pounds nitrogen) per acre in May to a 74-acre forested watershed in West Virginia. In the year following fertilization, nitrogen in the streamflow was increased only about 18 percent. Ammonium-nitrogen concentration was usually below 1 p/m and always below 2 p/m. Nitrate-nitrogen concentrations remained relatively low (below about 5 p/m) through most of the summer but rose as streamflow increased in the fall and reached 14 p/m during one storm period in September. Bengston's excellent review of forest fertilizing (1972) includes a discussion of its impacts on the environment.

On forested watersheds where overland flows are minimal, fertilizing is not likely to affect water quality adversely if direct application to streams is avoided and if application is restricted during spring snowmelt and heavy storms (Moore 1974). However, because different fertilizer materials are being applied at various rates during the current development of fertilization practices, streamwater should be monitored as a safeguard.

Herbicides

The risk of contamination from herbicides is a legitimate cause for concern. However, in many management situations their careful use has prevented problems. For instance, hand spraying streamside vegetation in New Jersey, Pennsylvania, and California, and basal spraying, stump treatment, and foliage spraying in West Virginia did not contaminate flow downstream (Krammes and Willets 1964, Lull and Reinhart 1967). However, after the experimental application of fenuron to part of a chaparral watershed in Arizona, relatively low concentrations of the herbicide persisted in the stream water for 2 full years (Davis and Ingebo 1970). After helicopter spraying in Oregon some herbicide was found in all streams in the sprayed area. This kind of contamination can be held to a minimum by avoiding direct application to large, slow-moving streams and marshy areas (Oreg. State Dep. Agric. 1967). The drift of herbicides during aerial spraying over western watersheds has caused major concern.

After considering the toxicity of the herbicide 2,4,5-T to animals, its biological degradation in the soil, and its incidence in streams after spraying, Montgomery and Norris (1970) concluded: "The hazard of 2,4,5-T in the forest environment is low when used according to tested procedures." Herbicides applied as aerosols are likely to drift; so this method of application is no longer recommended. Herbicides can be used to control vegetation but should be used only where known to be safe. Research may answer questions about safety that are now causing concern. Kunkle (1974) published some guides for proper use of herbicides and insecticides.

Insecticides

Insecticides also are used as tools in forest management. They pose a greater potential hazard to wildlife and man than herbicides. Present policy emphasizes minimal use of insecticides, the use of less persistent ones, substitution of biological controls wherever possible, and evaluation of environmental effects before insecticides are applied.

Fire

Burning the forest can increase both water yield and stormflow discharge. The amount of increase depends on the intensity, severity, and frequency of burning and the proportion of the watershed burned. Where much of the foliage is destroyed, interception and evapotranspiration are reduced; where the organic layers of the forest floor are consumed and mineral soil exposed, infiltration and soil-water storage capacities can be reduced. Fire may have greater effect on peak flows and erosion than harvesting, because it destroys the protective influence of the forest floor on a watershed that is completely burned.

Fires range from the intense conflagration that consumes everything in its path to the light surface fire that consumes only recently deposited, undecomposed leaf litter on the forest floor, and the range in effects of fire is just as great. Crown fires are generally more destructive than surface fires, but under some conditions a severe surface fire can kill all the trees and understory vegetation. The duration of fire effects ranges from a very short period to many decades, depending on the extent of the fire itself and the rate of recovery, which is influenced by both natural conditions and remedial measures applied by man.

Occasional fire has always been a natural occurrence in many forests; many present-day forest types owe their origin and perpetuation to fire. Thus what we call normal hydrologic behavior of many forested watersheds already incorporates some effects of fire.

Forests in the United States experienced a long period when fire frequency was greatly increased by actions of man. To some extent this is still true, but current prevention and control efforts generally keep fire from having the serious impact on forests that it had before settlement. When fires are less frequent, they are likely to be more severe because of the larger accumulation of fuel on the forest floor.

Forest areas are sometimes burned over to attain timber management or other objectives. These burns, called prescribed burns, are generally made during periods when burning conditions are moderate so that the impact on the forest floor and understory vegetation is less severe than the effects of large wildfires. No one has yet accurately determined or clearly documented (1) what forest types and soil conditions, (2) what sequences of weather conditions, or (3) what frequency of controlled burns will achieve the usual management objectives without also having adverse effects on watershed values and watershed protection. The needed evaluation is complicated by the sporadic nature of conflagrations, the infrequency of major storms, and the wide variation of watershed recovery potential after fires.

Recovery from fires, usually surface fires, may be rapid in the East—typically within a few years; regrowth after severe burning can be very slow—requiring decades in some forests.

Interception

Forest fires usually are classed as surface or ground type, or as crown fires; both types may kill trees. Severe fire may drastically reduce interception, even more than a timber harvest. As fire consumes or kills the principal intercepting surface, it can reduce summertime interception by hardwoods and conifers, respectively, from about 10 and 20 percent of rainfall to less than 5 percent. Most surface fires have little or no effect on canopy interception, but in Hawaii, a 17-percent increase in stormflow after the burning of fern cover from a watershed was associated with a reduction in "storage that was readily available for evaporation, such as interception storage." Infiltration and percolation were unaffected by the burn (Anderson and others 1966).

The maximum reductions in interception following surface fires are suggested by the amount of storage water in the litter of forest floors, discussed in the section on evaporation.

Infiltration, Overland Flow, Erosion, and Sedimentation

Infiltration, surface detention, and overland flow may or may not be affected by fire. In the humid East, fires severe enough to cause serious damage are rare under present forest protection. In the past, severe fires have reduced some surface areas, especially at higher elevations, to almost barren rock. In the drier West, the effect of fire is greater than in the East. The slow recovery of vegetation after fire at high elevations there results in greater accumulation of snow and more rapid melting, both of which add to hazards of spring flooding. Hot summer fires in the West can reduce the forest floor to ashes and thus set the stage for higher peak flows and greater water yield as overland flow.

The first year after a wildfire burned over three experimental watersheds in Washington, maximum streamflows were double the rate of flows before the fire, and debris flows in the same area were from 10 to 28 times as great as they were before the fire (Klock and Helvey 1976). In northern Montana, plot studies of runoff and erosion after broadcast burning following logging of mixed conifer stands recorded that runoff from snowmelt increased and remained high for four years after the burning, but erosion dropped back to normal volumes by the third year (DeByle and Packer 1972). Nutrients were lost in runoff only during the first year after the burning. Cole and others (1973) found losses from leaching were three to four times higher in slash-burned areas than in clearcut areas that were not burned.

Three studies of the effects of repeated burning on rates of infiltration in plots in the Ozark Mountains in Missouri showed that rates of infiltration into unburned surfaces were from about 60 to 800 percent higher than into soils of burned plots (Arend 1941; Auten 1934; Paulsell 1957).

Other research has shown less notable differences. Burns (1952) found that moderate burning on sandy soil in the pine barrens of New Jersey had little effect on infiltration; it increased the time required for 1 liter of water to infiltrate from 140 to 150 seconds. Hodgkins (1957) found no significant difference in infiltration rates between burned and unburned areas in loblolly-shortleaf pine stands in Alabama.

In northern Idaho, under an unburned stand of western hemlock with a duff layer about 2 inches deep, the infiltration rates exceeded the rates of applied rainfall, 3.5 to 5.2 inches per hour. In a stand broadcast-burned 17 years earlier, which had a thin and discontinuous layer of duff, the infiltration capacity was 2.8 inches per hour. However, this rate was exceeded only occasionally by natural rainfall (Holland 1953). In the Pacific Northwest, where thousands of acres of logging slash are burned annually for fire protection, slash burning has little effect on the hydrologic properties of the soil; its major impact is limited to severely burned spots that occupy only 3 to 8 percent of the total area (Tarrant 1956, Dyrness 1963). In the Idaho granitic batholith wildfire and slash-burned area reburns have been major problems (Megahan and Molitor 1975). Present policies designed to abate air pollution are leading to revision of slash-burning practices.

Burning affects overland flows very differently on different cover types. In the northern California brush zone, there was no consistent difference in runoff from sparsely covered chamise plots before and after burning; but runoff increased by a factor of 1.35 to 14.8 after burning of manzanita, oak, and shrub oak types (Anderson 1949a).

The effects of fires on both runoff and erosion depend on their frequency. Frequent fires can remove most of the protective cover, and thereby increase the potential for overland flow. In North Carolina, overland flow from a woodland plot burned twice a year for 9 years increased rapidly at first (Copley and others 1944). After 5 years' burnings, the annual runoff from the burned plot levelled off at an average of about 8 inches, equivalent to 22 percent of the rainfall (compared to less than 0.01 inch from the unburned control plot). The woodland plot burned twice annually lost 0.01 ton of soil per acre the first year, and 0.03 the next year; by the fifth year the loss was 3.90 tons; the next 4 years the loss averaged about 5 tons per acre—a substantial amount, but only about one-fifth the loss from plots where cotton and corn were growing. The unburned plot consistently lost only 0.01 ton per acre per year.

In the loessial upland of Mississippi, Meginnis (1935) found that for 103 rainstorms annual burning of a scrub oak forest resulted in overland flow from 54 storms, compared to 32 from a mature oak forest unburned for at least 7 years. In the 2-year study, less than 1 percent of the rainfall appeared as runoff in the mature oak plot, whereas the scrub oak plot produced 8 percent. Erosion from a scrub oak plot, typical of areas subject to severe cutting and annual fires, amounted to 0.33 ton per acre per year as compared to 0.02 ton from a mature oak forest. Conditions under the scrub oak were somewhat better than those in the North Carolina study; small quantities of litter were present but the mineral soil was exposed in many places (Meginnis 1935).

The development of a nonwettable layer of soil a little below the surface following fire is being intensively studied in California and elsewhere, and is discussed below in the section on southern California and Arizona chaparral. The extent to which this phenomenon occurs in the rest of the United States is not known; it probably occurs elsewhere (Bond 1968, DeBano 1969, Meeuwig 1971, Scholl 1971) but almost certainly with less noticeable consequences than in the chaparral, where the effect of fire on floods is evident. However, this nonwettability of soil may promote overland flow in any area that has the combination of periodically repeated fires, coarse-textured soils, and high intensity rainstorms.

The effects of forest wildfire and prescribed burning on erosion and sedimentation depend on the severity of the burn, the erodibility of the soil, the potential for recovery of the vegetation, and the kind of storms that follow the fire. In humid forest regions, occasional wildfire and infrequent prescribed burning do not produce overland flow and hence do not cause erosion. Thus summer prescribed fires in Georgia's lower Piedmont, which killed 86 percent of the understory hardwood stems and provided for successful regeneration of pine, had negligible effect on soil movement. "Almost all of the decomposed litter was left to protect the soil; even some of the partially decomposed litter remained unburned. The top layer of mineral soil also has organic matter incorporated in it and is receptive to rainfall absorption" (Brender and Cooper 1968).

Studies of prescribed burning on much drier ponderosa pine sites in California and Arizona showed no noticeable effect on overland flow and erosion. In both studies a sufficient layer of organic material remained after the fire to protect the soil (Biswell and Schultz 1957, Cooper 1961). The bulldozer trails created in controlling the burns contained some overland flow. In a mixed-conifer forest, prescribed burning increased both surface runoff and erosion (Agee 1973). In another study in Arizona, erosion occured only where less than 60 percent litter cover remained after burning (Pase and Lindenmuth 1971).

Massive wildfires in western forest regions have accelerated both erosion and sedimentation. In northern California watersheds, a 10-year average of 34 acres per square mile of wildfire increased sediment discharge 2.3 times (Wallis and Anderson 1965). Seventeen years after the Tillamook Burn in the Wilson River Watershed of Oregon, the annual rate of sediment discharge was 500 tons per square mile, five to eight times that of nearby unburned forested watersheds having similar geology (Anderson 1954).

Similarly, presence of brushfields at high elevations in the Sierra Nevada in California has been attributed to the spread of autumnal fires set by sheepmen to "green up" the next season's growth. Recent analysis shows those brushfields produce 55 percent more sediment (measured as deposition in reservoirs) than coniferous forest stands (Anderson 1974). In southern California too, "old fires," fires that had burned 15 to 60 years earlier, were still accelerating reservoir deposition. During the March 1, 1938 flood, thrice-burned areas had sediment rates four times those of areas that had no old fires (Anderson and Trobitz 1949).

When trees, ground vegetation, and forest floor are completely destroyed by fire, high-intensity rainfall usually produces great quantities of sediment. On the 242-acre Dog Valley experimental watershed established on such a burn on the east side of the Sierra Nevada near Reno, Nevada, a single storm produced 16,100 cubic feet of sediment, or about 2,500 tons per square mile. Nearby unburned areas produced scarcely a trace of sediment (Copeland 1965). During the same year, only low-intensity rain and snow fell in another part of the burn; maximum sediment concentration in the streamflow did not exceed 78 p/m (Anderson 1962a).

Substantial erosion followed an intense fire on 60 acres of a 318-acre watershed in the South Fork of Workman's Creek in Arizona. The fire consumed litter and ground vegetation and killed all but a few ponderosa pine; it was followed by a 3.8-inch rain, one of the heaviest on record in that area. The burn was confined to the flattest slopes; unburned vegetation trapped and held half of the sediment, and tree growth and rocks prevented gully formation. In spite of these favorable conditions, sedimentation was about 1 acre-foot, equivalent to about 33 tons per acre of burn (Rich 1962).

Hot fires are not always followed by great yields of sediment. Soil type, revegetation, topography, and meteorological events may nullify fire effects on erosion. Erosion indicators on a fire-denuded area of the Douglas-fir region show that the exposed "shot-loam" soil maintained sufficient infiltration capacity to prevent most overland flow; growth of vegetation during the first year after the fire provided additional effective control (Sartz 1953).

Soil-Water Storage

Fire reduces the capacity for soil-water storage when humus layers and organic material in the mineral layers are burned, or when soil exposure augments the oxidation of organic matter. In the surface 2 inches of soil, severe surface fires can reduce the capacity about 1/4 inch (Dyrness and others 1957). When an overlying 2-inch layer of humus has been destroyed, the total reduction of water storage capacity would be about 1 inch. Obviously crown fires drastically reduce evapotranspiration and opportunity for soil-water storage; the result is similar to that of cutting the forest.

Evapotranspiration

A light ground fire may have little or no effect on evapotranspiration; a hot crown fire may have an effect equal to or greater than clearcutting, for it may destroy the forest floor, the tree canopy, or both. A reduction of interception and transpiration may be partly offset by increased evaporation from the forest floor, particularly if seasonal rainfall comes as many low-rainfall storms.

Quantity of Streamflow

Fire-prone brushland in California and Arizona can be a source of increased streamflow. For example, burning the Fish Creek Watershed in southern California killed almost all of the chaparral, and annual streamflow increased by 2.5 inches the first year after the fire. The increase declined to 0.7 inch by the sixth year, for an average increase of 29 percent for the 6-year period (Hoyt and Troxell 1934). In the Santa Ynez watershed, however, where sediment was eliminated from the total volume of water and sediment, a major fire did not increase total annual flow (Anderson 1955). The burning of a woodland-brush experimental watershed in Arizona sharply increased water yield: over a 36-month period before the fire, accumulated precipitation of 70 inches had produced 3 inches of flow; in 21 months after the fire, 50 inches of precipitation produced 16 inches of flow (Price 1962).

The Tillamook Burn in 1933 in Oregon (partly reburned in 1939 and 1945) increased the total annual water yield of the Trask and Wilson River watersheds (143 and 159 mi^2, respectively) by 9 percent (8 inches) and July-through-September flow by 16 to 20 percent (0.5 to 0.7 inch) for the first 16 years after the 1933 fire (Anderson 1975b).

In 1970 fire killed virtually 100 percent of the surface vegetation on the Entiat Experimental Forest in north-central Washington. Helvey (1972) reported increases in streamflow the first year after the fire that averaged 3.5 inches for three watersheds of about 2 mi^2 each; increases came mostly during spring snowmelt and during the summer months. Debris flow was not measured, but more than 3,000 yd^3 mi^2 was deposited at the mouths of the watershed; this included some boulders as large as 6 ft in diameter (Helvey 1973). Stream chemistry was only moderately affected. Nitrate-nitrogen was increased by a factor of eight, but averaged only 0.04 p/m, whereas cations actually decreased because of dilution by the increased streamflow (Tiedemann 1973).

Peak Flows

The Tillamook Burn also increased annual peak flows from the Trask and Wilson River watersheds. Their annual peak discharge increased about 45 percent the first year after the burn, compared to the adjacent slightly burned Siletz watershed (200 square miles in area). The increase declined to 10 percent by the seventh and eighth years after the burn with no apparent increase thereafter (Anderson 1976b).

A crown fire on the 318-acre South Fork watershed in Arizona killed all but a few of the pine and Douglas-fir trees and consumed litter and ground vegetation. Predicted peaks for an unburned condition and actual peaks after the burn for the four highest flows during the first summer were:

Predicted	Actual
ft^3/s	ft^3/s
8	78
2	19
3	16
1	21

Peak flows increased 5 to 15 times, and they continued high through the second summer. Winter peaks did not exceed preburn height (Rich 1962).

Snowmelt flood peaks may be increased by burning the shade-producing trees. We have already noted that burning over half of a watershed on the east side of the Cascade and Blue Mountains areas in Oregon and Washington may increase peaks by about 11 percent (Anderson and Hobba 1959). Both deliberate broadcast burning and frequent wildfire in logged-over areas may have contributed to the increases from rain-on-snow floods reported. In Idaho, after 18 percent of the Clearwater drainage was burned in 1919, spring flood peaks were 11 percent greater and the average peak flow came 14 days earlier. The Columbia River flood in the spring of 1948 may have been due partly to the large areas of burned-over forest in the headwaters. At the time 31 National Forests occupied about one-third of the basin; more than 5 million acres of them had burned, 11 percent of their total area; many of these lands had recently burned over two or three times (U.S. Dep. Agric., For. Serv. 1950).

The classic test of the effect of burning on snowmelt peak discharges was conducted at Wagon Wheel Gap in Colorado some 50 years ago. There the forest cover was cut and burned on one watershed and left untouched in a paired basin. Peak flows from the treated basin decreased by as much as 50 percent the first two years after the treatment, and were lessened each year by the recovering vegetation until by the seventh or eighth year there was little difference in the peaks from the burned and untreated watersheds (Bailey 1948).

Prescribed burning has been common practice in the Atlantic Coastal Plain for many years. It is applied to reduce brownspot infection of longleaf pine seedlings, competition from hardwoods, or fire hazard. Burning may be repeated every 3 to 10 years. There has been no evidence that this practice results in any great increase in peak flows.

A substantial reduction in the area burned by wildfires has diminished the hydrologic impact of fire. From 1931 until 1936, an average of 42 million acres of forest land burned annually; from 1961 to 1966, the average was one-tenth as much, 4.3 million acres (U.S. Dep. Agric., For. Serv. 1967a), or about 0.4 percent of the total forest area.

Summary

The effects of fire on forest-produced water differ. Light, surface prescribed burns or wildfires have little impact. Wildfire that consumes the forest floor and kills the trees and other vegetation over a large area has major impact on stormflows, erosion, sedimentation, and the quantity of streamflow. Duration of effects is strongly influenced by the rate of revegetation. For the country as a whole, the current level of fire protection has greatly reduced the hydrologic importance of fire from what it was several decades ago. Where severe, widespread wildfire still occurs, as in some areas of the West, fire is still a serious threat to watersheds.

Grazing

Grazing is an annual harvest. Whether its effects become cumulative and reach hydrologic significance depends upon the intensity of grazing, the season of use, and the sensitivity of the land. The most recent survey of the extent and importance of forest grazing was made by the U.S. Forest Service (U.S. Dep. Agric., For. Serv., For.-Range Task Force 1972). This survey estimated that in 1970 about half (85 million acres) of the western forest, and about four-tenths (161 million acres) of the eastern forest were grazed. This study reported exploitative grazing (as opposed to acceptable management) on less than 4 percent (3 million acres) of the area grazed in the western forest, and on 45 percent (72 million acres) of the area grazed in the eastern forest. In Colorado Basin, reduced livestock numbers, improved range management, and erosion control have effectively reduced sedimentation; Hadley (1974) attributed the 50-percent reduction of suspended sediment load carried by the Colorado River to such management.

The grazing of forested watersheds has been the subject of much heated controversy for many years. Some quantitative effects on hydrologic processes have been reported.

Interception and Evapotranspiration

The consumption of foliage by animals in the forest is rarely severe enough to reduce interception significantly or to curtail evapotranspiration; grazing of ordinary pasture land may have greater effect on these processes. Continued heavy grazing can eventually kill or reduce the vigor of trees; either effect will decrease both interception and evapotranspiration.

Infiltration, Overland Flow, Erosion, Sedimentation, and Peak Flow

Woodland grazing may sharply reduce infiltration and increase overland flow by soil compaction. Stoeckeler (1959) measured the following infiltration capacities in ungrazed and grazed oak and conifer stands in Wisconsin:

	Infiltration capacity *(in/h)*
Cover:	
Ungrazed native oak	7.46
Grazed native oak	0.05
Ungrazed Scotch pine	11.02
Grazed Scotch pine	1.25

The effect of grazing on infiltration may be much less under other conditions. In some western conifer types, grazing is localized in forest openings and meadows; in such areas infiltration capacities may not be affected in any widespread, continuous manner. On the Manitou Experimental Forest, for instance, infiltration rates "were always high" under litter-covered soil beneath a canopy of ponderosa pine; they averaged 22 percent higher than rates under open-grown pine with a grass understory, and 39 percent greater than on grassland (Dortignac and Love 1961). No erosion was apparent under closed canopies that had a ground cover of tree litter. Lower infiltration rates and greater potential for both grazing and erosion were usual in open forest with a ground cover of herbaceous vegetation and pine litter, and in open glassland parks that supported herbaceous vegetation.

About 8-1/2 percent of the rainfall in eight intense storms appeared as overland flow on a grazed watershed near LaCrosse, Wisconsin. Overland flow occurred only twice on an ungrazed area, and then in insignificant quantities (Hays and Atkinson 1939). A later study at the Coulee Experimental Forest, also near LaCross, showed that only 3 percent of the precipitation from five major storms appeared as overland flow from a heavily grazed woodland. Ungrazed forested watersheds produced no measurable amounts. Peak flow from the grazed area was 0.12 inch per hour or 77 $ft^3/s/mi^2$. Maximum sediment concentrations were 55,900 p/m from the grazed, and 100 p/m from the ungrazed area (Sartz 1976). Another grazed hardwood watershed in Wisconsin lost soil at the rate of 0.1 ton per acre per year, perhaps four times the rate from ungrazed woodland but considerably less than from cropland (Hays and others 1949).

In a more intensive study at Coweeta a 145-acre forested watershed was grazed from May to September for 9 years by an average of six head of cattle. By the end of the first growing season, practically all herbaceous forage and much of the hardwood understory had been consumed, and supplementary feeding was necessary. For a number of years there was little apparent effect on runoff, but by the end of the eighth grazing season, overland flow moved directly into the stream and the frequency and magnitude of peak flows increased immediately and sharply. Before grazing, 2 inches of rainfall (between beginning of flow and peak flow) produced a discharge of about 18 $ft^3/s/mi^2$; after 9 years of grazing the peak was 32 $ft^3/s/mi^2$. Comparable values were 32 and 120 $ft^3/s/mi^2$ for a 4-inch rainfall (Johnson 1952). This grazing treatment hardly affected sediment yield until overland flow finally made its way to the channel in the ninth year of grazing. Shortly thereafter the maximum turbidity in one storm was 108 p/m as compared to 30 p/m from an adjacent ungrazed forested watershed (Johnson 1952). Hursh (1951) attributed to the delay to the accumulation of forest-litter plugs along natural drainage lines; eventually the surface water increased enough to carry away the plugs and develop uninterrupted channels to the main stream.

Dissmeyer (1976) reported that overgrazing in a large river basin in the South caused 92 percent of the estimated accelerated erosion. In the Boise River Basin in Idaho, Rennar (1936) reported that in timber types overgrazing had been responsible for much of the watershed erosion damage.

Summary

Properly managed forest grazing has little adverse effect on surface hydrology or erosion. Overgrazing reduces infiltration and increases overland flow. Voluminous evidence shows that overgrazing increases erosion greatly. Unless it is heavy enough to eliminate much of the forest, grazing has only slight effect on the quantity of streamflow; it can have much greater effects on stormflow volumes and peaks, erosion, and water quality.

Forest-Land Disposal of Waste

The disposal of municipal and industrial wastes may someday be an important use of forest land (Sopper and Kardos 1973), and, depending upon circumstances or emphasis, the fertilizing of timber crops with wastes may become an accepted forest practice (Gagnon 1973). The areas of forest land used for disposal of waste can satisfy an important need, especially for disposal of sewage from rural communities, even though such use will require only a very small proportion of all forest land. Waste disposal can have significant hydrologic consequences. Use of wastes on the land, under careful control and management, can (1) dispose of the waste, (2) renovate and recycle water, (3) recycle nutrients to increase forest or understory vegetation production, and (4) in some areas serve to create "green belts" for forest fire hazard reduction.

Seabrook Farms pioneered sprinkler irrigation of woodland in the sandy coastal plain of New Jersey in 1949 (Thornthwaite 1951). They discovered early the advantages of using woodland for waste disposal: with an open-field spray, 2 inches of water a day saturated the soil to plow depth and started overland flow; in contrast, when more than 150 inches of water was applied over a 10-day period to a wooded area only 400 feet away, there was no noticeable saturation. Although about 400 to 600 inches of water was applied annually for 19 years, there has been no overland flow. The trees did not survive, but the protective forest floor, augmented by organic debris in the waste water, maintained a high infiltration rate.

In areas where infiltration capacity is low, polluted water has been purified by slow overland flow downhill through forest litter, humus, and ground vegetation. Suspended and dissolved solids are filtered out and converted into humus (Mather and Parmelee 1963).

Effluent from sewage treatment has been successfully sprayed in woodland at the Pennsylvania State University at intensities of 1 to 4 inches depth per week. Water samples collected at the 12-inch soil depth under a red pine plantation showed a 95- to 98-percent reduction in concentration of alkyl benzene sulfonate, a constituent of detergents, and reductions of 68 to 88 percent in nitrate N, organic N, K, Ca, and Mg. The average concentrations of all constituents in the percolate at 12 inches were considerably less than the allowable limits set for drinking water by the U.S. Public Health Service. With a 2-inch weekly irrigation rate from April 8 to November 18, the total weight of constituents applied was equivalent to 2,500 pound per acre of 10-10-10 (NPK) fertilizer (Parizek and others 1967). After nine years of irrigation with treated municipal wastes, no detrimental effects on the forest soil were observed (Richenderfer and others 1975).

Sprinkler systems are now employed extensively in disposal of waste water. By 1957, 250 systems were operated by food processing plants and 18 operated by pulp and paper mills. In 1972, 75 installations in Pennsylvania were spraying municipal wastewater on the land and another 10 to 15 were in planning and design stages (Rhindress 1973).

Waste water and sludge may prove to be useful in reclaiming surface mines (Lejcher and Kunkle 1973). Results of recent tests (Sopper 1975) indicate the revegetation of anthracite coal refuse is possible through the application of treated municipal wastewater and liquid digested sludge. The feasibility of using wastewater to irrigate greenbelts for the reduction of wildfire hazard in California chaparral is being studied (Youngner and others 1973). Irrigation at rates of 1.75 in/week or more maintained moisture content of Ceanothus at levels above 70 percent, where they are not readily flammable.

Much research and development must be completed before the application of wastes to forest land can become widespread or routine. Evans (1973) has suggested 19 research needs; these include economic and social consideration; techniques for handling waste materials; pollution effects on land, groundwater, and streams; effects on animal and plant populations, including crops; infiltration and storage capacities of different soils; cold weather problems; and the need for better systems for monitoring soil and water and adequate standards and guidelines for resultant water quality.

Insects, Diseases, and Weather

A tree killed by insects, disease, or windthrow affects the hydrologic cycle much the same as if it had been cut down; interception and evapotranspiration are reduced or stopped but infiltration usually is not affected. The hydrologic changes differ in detail, and, of course, there is none of the machine-caused site disturbance that usually accompanies timber harvesting.

Insects kill more trees than any other agent; weather (wind, ice and snow, lightning, and drought), and disease kill markedly fewer trees.

The estimated mortality for 1952 was (U.S. Dep. Agric., For. Serv., 1958):

	Growing stock	Live sawtimber
	Million ft^3	*Million fbm*
Cause:		
Insects	1,000	5,041
Weather	843	3,387
Disease	773	2,242
	2,616	10,670

A reassessment in 1970 (U.S. Dep. Agric., For. Serv., 1975) was that natural mortality of sawtimber amounted to 15.3 billion board feet annually. If confined to one area, these losses would be equivalent to more than 2 million acres of forest destroyed, and their effect on streamflow would be enormous, as indicated by the individual effects of fire, insects, and blowdown on streamflow amounts and floods.

These damages are scattered throughout the forest land of the country. Mortality in any given affected area is usually caused by a single disease or is confined to a single insect-ridden species, and not all individuals of that species succumb. These conditions modify the impact so that it probably is comparable to or less than the total effect from selection cuttings. This would be true particularly for mixed hardwood stands in the East or mixed conifer stands in the West. Although chestnut blight reduced the production capacity of the hardwood forest north of Maryland by 15 to 50 percent (Boyce 1938), it occurred in mixed stands and was a progressive disease, requiring 1 to 10 years to kill a tree. Streamflow would be barely affected if surrounding trees continued their growth and maintained evapotranspiration rates. Sometimes the effect of damage caused by a single insect species or disease can be singled out and measured, as it was when beetles killed most of the spruce and pine on the 762-square-mile White River drainage in Colorado. Love's analysis (1955) indicated an annual increase in streamflow of about 2 inches in the 1947-51 period following the kill. Total increase in two large river basins for the 25-year period 1941 through 1965 was 22 and 14 percent, or 37 and 30 inches (Bethlahmy 1974). Peak flows were 27 percent higher in the west-flowing White River, but only 4 percent higher in the north-flowing Yampa River.

Catastrophic winds, massive earthslides, and snow avalanches that fell trees over large areas may have greater effects on water than attacks by insects, especially the effects on water quality caused by erosion and sedimentation. The 1938 hurricane in New England destroyed about half the merchantable timber in a swath 80 miles wide extending from Rhode Island and eastern Connecticut to the White Mountains (Barrett 1962). That storm doubtless increased water yield (Patric 1974). Eschner and Satterlund (1966) showed how extensive blowdown in the Adirondacks from a storm in 1950 interrupted a 39-year trend in which the annual water yield from a protected watershed had gradually declined by about 7.7 inches. The blowdown and continuing mortality of storm-weakened trees during the next several years increased water yield to near the original level.

The effects on erosion and erosion-induced turbidity of streamflow are generally minimal; water temperature may be locally affected, and water chemistry may be altered temporarily by leaf fall and accumulation of debris in channels.

The total effect of forest damage by insects, diseases, and weather is usually incorporated into what we accept as normal variability of streamflow.

Minimum-Treatment Management

In land-use planning, the point is frequently made that one possible alternative is to apply no management at all. This practice of leaving lands in their natural state is being applied to more than 11 million acres of officially designated Wilderness Areas, more than 4 million acres of Primitive Area managed as wild lands, and to many other areas. What are the effects on water of such minimum-treatment management?

If complete protection were possible, the trend in forest succession would be toward the climax type, which probably occupies the site more completely than any other. Under this condition, on-site use of water would be at or near the maximum, and erosion and sedimentation would be at a low level in most areas.

Even though protected from disturbance by man, the forest cover may be partly or completely destroyed by fire, insects, or wind, and the water regime may be affected in ways that have already been discussed. The effects of fire and insect attack may be greater than in the managed forest because of the absence of directed prevention and control measures, planting, or other activity for site rehabilitation.

III - SPECIAL PROBLEMS

Unusual conditions in some areas in the United States present special forest-water problems. Though the hydrologic processes already discussed apply in these situations too, we believe special attention to them is merited. The following four situational problems deserve brief special attention:

1. Southern California and Arizona chaparral — an extreme fire-flood-erosion situation
2. Wetland Forests — extreme water abundance
3. Phreatophytes — extreme water use
4. Surface Mining — extreme site disturbance

Southern California and Arizona Chaparral

Of the 759 million acres of forest land in the United States, about one-third is classed as noncommercial because it does not yield wood products. About 101 million acres of this land is in the West. Most of this forest has the same relation to floods, erosion, and sedimentation as the commercial forest does, but about 16 million acres of it behave quite differently. Forests on this land burn readily and completely and thereby set the stage for disastrous floods that usually produce huge volumes of sediment. This is the chaparral area of southern California and Arizona, the country's most inflammable forest and, per unit area, the greatest source of forest-flood damage. In some areas, even unburned chaparral cannot stabilize the soil that supports it. These conditions also exist in varying degrees along the central coast of California and in a belt around the great valleys.

Of the two areas, California's chaparral presents the greater problem. Its 17 million acres of chaparral and associated types have a Mediterranean climate—dry, hot summers and mild, wet winters. Annual precipitation averages about 27 inches but ranges from 12 to 48 inches. Nearly three-fourths of the rain comes during December through March; there is almost none during the summer. Some of the highest rainfall intensities and amounts in the United States have been recorded in this area: 1.02 inches in 1 minute, 11 inches in 7.3 hours, 26 inches in 24 hours, and 43 inches in 3 days (Anderson 1964).

Much of the problem of the chaparral area is caused by its location. Chaparral occupies roughly 70 percent of the mountain ranges fronting the southern third of California's coast. Below it are 300 square miles of valuable properties: homes, orchards, towns, cities, highways, railroads, and industries.

Flood damage can be immense. In the 1938 flood in the Los Angeles area, 87 lives were lost, and property damage was estimated at $79 million. Potential average annual damage there had been estimated at $34 million (U.S. Senate Sel. Comm. Natl. Water Resour. 1960a). The Flood Control Acts of 1936 and 1945 authorized federal flood control expenditures totalling more than $400 million (Hoyt and Langbein 1955). By 1969, about $1 billion had been spent on flood control structures in the Los Angeles area (Wood 1970). Damage following fires and expenditures for flood control attest to serious and closely related problems of fire and flood control.

Fire-Flood-Erosion

Fires followed by the January-February storms in 1969 were responsible for 47 flood deaths (Calif. Dep. Water Resources 1970). Rice and Foggin (1971) and Scott (1971) described the sedimentation consequences of the storm. More than 200,000 cubic yards per square mile of watershed was measured in individual debris basins (Scott 1971).

Colman (1953a) described three other fire-flood-erosion sequences. On New Year's Day in 1934, less than 2 months after fire burned 7 square miles of chaparral in the mountains above the cities of Montrose and La Cresenta, a severe storm struck. The flood that followed killed 30 persons, devastated several towns, and caused $5 million damage; unburned watersheds nearby produced only normally high streamflow.

In July 1945 an airplane crashed into the chaparral of the upper Santa Ana River watershed, and started a 4,000-acre fire. Although this burn covered only 1/25th of the watershed, thunderstorms that autumn caused mud and rock flows that interrupted the operation of three hydroelectric plants and disrupted irrigation schedules on 10,000 acres of citrus orchards.

In 1950, the fire-flood-erosion sequence was most convincingly demonstrated. A fire on July 4 in the hills 4 miles north of Yucaipa, California burned about 630 acres of chaparral. Two days later a severe thunderstorm struck the burn and areas surrounding it; mud and boulders poured from the burned area in quantities that blocked roads and incurred several thousands dollars' worth of damage. There were no flood flows or erosion on adjacent unburned drainages (Colman 1953b).

Such damaging fire-flood sequences had led to record expenditures for fire control. The average annual per-acre costs in the chaparral zone are several times the national average (Davis 1959).

Streamflow records from experimental watersheds in the San Dimas Experimental Forest before and after fires give some indication of fire's effect. After a fire in 1938, two storms from an unburned watershed produced peaks of 7 and 17 $ft^3/s/mi^2$; a watershed only 3 percent burned had peaks of 12 and 20 $ft^3/s/mi^2$; and one 26-percent burned had peaks of 26 and 55 $ft^3/s/mi^2$. After the 1953 burn, a heavy storm on an unburned watershed caused a peak of 5 $ft^3/s/mi^2$; on one 3-percent burned, a peak of 20 $ft^3/s/mi^2$; and on one 32-percent burned, a peak of 429 $ft^3/s/mi^2$. With wet soil conditions and smaller storms, peaks from burned watersheds were 1.2 to 15.6 times greater than peaks had been when the watersheds were unburned (U.S. Dep. Agric., For. Serv., San Dimas Exp. For. 1954).

The 1960 fire at San Dimas produced even greater differences. For two of the larger watersheds, 740 and 875 acres, peak flows from a 4-inch storm before the fire were 0.76 and 4.4 $ft^3/s/mi^2$, respectively; a similar storm after the fire gave comparable peaks of 660 and 880 $ft^3/s/mi^2$ (Krammes and Rice 1963). Statistical relations between flood peaks and sedimentation and forest fires, and the recovery of vegetation after fires, have provided a basis for intensified fire protection (Anderson 1949b).

Tremendous discharges from freshly burned areas may be due partly to fire-derived nonwettable layers of soil. These layers are formed when large soil temperature gradients cause vapor and gases containing hydrophobic substances to move downward from the surface organic matter into the surface soil. There they condense on soil particles and inhibit infiltration. The depth and thickness of the water repellent layer depend on the intensity of the fire and the amount of vegetation and litter consumed (DeBano and Rice 1973). Soil texture also seems to be a factor; clay soils are less susceptible than sandy soils (DeBano 1969). Similar repellency has been reported for soils under both natural and burned chaparral in Arizona (Scholl 1975). Small-scale research tests indicate that chemical wetting agents may be useful in reducing overland flow and erosion from nonwettable soils, but recommendations cannot be made yet for general application (Krammes and DeBano 1967). A large-scale test failed to reduce overland flow and erosion during the 1969 flood (Rice and Osborn 1970).

Water repellency of soils developed by fire may prove an advantage in reforestation of burns. DeBano and Rice (1973) have suggested that if stock is planted in contour furrows, the extra runoff from the inter-furrow repellent areas will be trapped in the furrows and provide moisture to nurture the new seedlings. It would seem also that alternate furrows for trees and dense contour seeding, such as rows of barley or mustard, would accomplish both immediate erosion control and reforestation.

Erosion Without Fire

Along the Los Angeles front of the San Gabriel Mountains in southern California, watersheds long unburned steadily contribute sediment to stream channels. On south-facing slopes of 90 percent in the Los Angeles River watershed, that have a cover density of 65 percent, debris moves into the channel at an average annual rate of 3.56 tons *per acre*. A little more than half of this is deposited during the dry season; many of the slopes lie at angles steeper than the natural repose for dry material. "A breeze that shook the brush was enough to start a minor slide. . ." During the rainy season most deposition occurred after soil-moisture storage opportunity was satisfied. Debris movements from north-facing slopes of 70 percent and from north- and south-facing slopes of 55 to 60 percent averaged from 0.2 to 0.72 tons per acre per year (Anderson and others 1959).

Highly erodible road slopes in southern California also pose problems. Erosion from road fills has averaged from 6 to 10 times that from adjacent nonroad areas (Anderson and Wallis 1965). Special erosion-prevention procedures must be used (Kraebel 1936). On the Angeles National Forest they include reducing volumes of cuts and fills by using retaining walls and cribbing, reducing design speeds to meet minimum traffic needs, fitting road alignment to topography, keeping road gradients to a minimum, and contour-trenching, staking, and seeding of fill slopes (Usher 1961).

The methods for stabilizing road-fill suggested by Kraebel (1936) were used on the road to the Palomar Mountain Observatory in southern California (Juhren 1949). The road-fill treatments consisted of contour wattling (bundles of brush 6 to 7 feet long and 4 to 6 inches in diameter placed end to end in contour trenches) together with seeding of barley or ryegrass, using wheat straw between rows, and planting willows, mulefat, trees, and shrubs. In the 1938 flood, erosion from unprotected slopes was as much as 680 cubic yards per acre, equivalent to 5 inches' depth over the area. The only fills that did not erode were those treated. Since many of these improved methods also reduce costs of road maintenance, there is hope for prevention of major increases in sediment discharge from large road construction projects.

Erosion After Fire

Sedimentation accounts for much of the fire-flood-erosion problem in the chaparral of southern California. During the summer following the Woodwardia fire in October 1959, dry creep from steep slopes increased by 4 to 17 times. Erosion directly related to the fire ranged from 2.2 to 24.7 tons per acre the first year; south-facing slopes yielded the most debris—10 times the preburn rate. About 89 percent of the eroded material came from surface sloughing during the dry season (Krammes 1960).

Increases in rainfall erosion were even greater in another area. After the January 1954 storm on the December 1953 burn at the San Dimas Experimental Forest, an average of more than 0.6 inch of ash, soil, gravel, and decomposed rock was removed from side slopes by sheet and rill erosion. In addition, the material from channel erosion gave an estimated erosion rate of 55,500 yd^3/mi^2 of burned area. The normal erosion rate for that drainage is about 2,000 yd^3/mi^2 per year (U.S. Dep. Agric., For. Serv., San Dimas Exp. For. 1954). These values are not exceptional for this part of the country. Forty-one watersheds in southern California, from 1 to 1,465 square miles in area, produced annual averages of 600 to 9,770 cubic yards of sedimentation per square mile. After one-fourth of the watershed was burned, estimated production from a 100-year flood was 9,900 to 113,000 cubic yards (Anderson 1949b). Maximum yearly sedimentation of 71 debris basins guarding the San Gabriel Mountain front has ranged from 3,500 to more than 200,000 yd^3/mi^2 (Los Angeles County 1970).

Control and Rehabilitation

Flood and erosion control require prevention or control of wildfire. Land managers agree that this requires construction of firebreaks and some managers recommend reduction of fuel by converting chaparral covered land to grassland wherever feasible. This conversion, however, may reduce the opportunity for soil-water storage. Conversion from chaparral to grass cover at San Dimas increased the average daily evapotranspiration rates during the rainy season from 0.048 to 0.059 inch, an average annual increase of about 2 inches. Most of it occurred from January to April when scrub oak growth was slow and annual grass growth relatively rapid. Evapotranspiration from grass practically ceased when the grass matured in early summer, having used all available water to a depth of 2 1/2 feet and created some water storage opportunity to depths of about 7 feet. During summer evapotranspiration losses were far greater from the chaparral (0.073 compared to 0.034 inches per day) and continued until all available moisture in the 12-foot soil depth had been utilized (Rowe and Reimann 1961). The soil-water storage opportunity on deep soils under chaparral is almost always more effective for flood control. During the January to April rainy season, the somewhat greater soil-water deficits built up by the greater evapotranspiration under grass are quickly satisfied in any flood-producing storm. The soil slippage problem in steep grassland is discussed later in this section.

Burned-over watersheds have such high damage potential that they must be rehabilitated immediately. Annual ryegrass, broadcast seeded, can provide a quick ground cover that persists for a few years but does little to moderate damages from peak flows. Wheatgrasses (long-lived, drought-tolerant bunchgrasses) have performed well in tests. They mature somewhat later in the spring or summer than many other grasses —an important consideration in planting for fire control and for a fuel-break cover (Bentley 1967).

The treatments following the 1960 fire at the San Dimas Experimental Forest are a good example of erosion control (Rice and others 1965). Tested were broadcast seeding annual and perennial grasses, bulldozing wide contour trenches (Bailey and Croft 1937), building check dams in channels, and planting barley in contour furrows. The total debris produced during the first year after each of four treatments was:

Treatment:	*Yd^3 acre*
None	29
Contour trenches	14
Channel check dams	17
Contour planting	10

The check dams filled quickly to their design capacity during the first two storms. Contour trenches, although large, could not be spaced closely enough to provide adequate storage for runoff volumes from large storms. Planting barley on the contour was the most successful treatment: seeded at the rate of 150 pounds per acre and fertilized, it prevented appreciable overland flow, but the treatment deteriorated rapidly 2 years after sowing (Krammes and Rice 1963). Standard rates of grass seeding, because of steep slopes and surface instability, accomplished little for it did not produce a total vegetative cover significantly greater than that on unseeded controls. A high-density (20 lbs/acre) sowing of a mixture of annual grasses did reduce erosion by 16 percent. The average cost of helicopter sowing on large areas is about $1 per acre plus cost of seed (about $4 per acre for high-density annual mixed and $13 for perennial). The cost of barley in contour rows is about $140 per acre. This measure must obviously be restricted to critical erosion areas (Corbett and Green 1965).

Soil slippage in brushland converted to grassland following a forest fire had produced 3 to 7 times as much erosion by two large storms as occurred in naturally recovering brushland (Rice and Foggin 1971).

Removing flood debris and seeding of watersheds as an erosion control measure following a fire can cost more than fire suppression. For the 1960 fire at San Dimas, the fire suppression cost (Federal only) was $800,000, whereas cleanup and erosion control cost $917,000. In the first 2 years after the fire, debris production amounted to 24,000 cubic yards per square mile. During the same period, 33 unburned watersheds in the surrounding San Gabriel Mountains produced 6,000 cubic yards per square mile, while 16 partially or completely burned ones produced 40,000 cubic yards per square mile (Rice 1963).

To prevent erosion from unburned watersheds in southern California, various reinforcements of existing vegetation are recommended. To reduce sliding from upper slopes, species should be found that will convert the original single-stemmed vegetation to a multi-stemmed but deep-rooted cover. On slopes that exceed the angle of repose, the soil mantle can be tied to the underlying rock by additional vegetation without reducing the effectiveness of the existing deep-rooted brush. To prevent gullying of colluvial deposits, overland flow should be spread by mechanical means or by planting multi-stemmed vegetation; widely-spaced, single-stemmed vegetation is relatively ineffective (Hellmers and Anderson 1955).

No rehabilitation measure yet devised gives immediate protection comparable to unburned chaparral. Debris basins or other protective devices are often needed to reduce damage after fire.

Arizona Chaparral

Arizona has about 4 million acres of chaparral, varying from dense stands to open, desert-like scrub. Annual precipitation on this area is somewhat less than that on the California chaparral; it ranges from 16 to 25 inches. Most of it comes as winter rainfall; but in contrast to California, summer storms account for about one-third of the total annual precipitation and those storms can cause flooding and erosion.

The Arizona chaparral, like its California counterpart, can be completely consumed by fire. Peak flows and sediment production increase immediately. After an intense fire, one of the 3-Bar Experimental Watersheds produced 40,000 tons of sediment per square mile over a 6-month period; unburned watersheds produced from negligible amounts of sediment over periods of 2 to 3 years to as much as 500 cubic yards of sediment per square mile from two storms of 1 to 2 inches (Glendening 1959). With 70 inches of accumulated precipitation, accumulated sediment was about 200 tons per square mile in the 36 months before the fire; in the next 21 months after the fire, accumulated sediment increased 100-fold to 22,000 tons per square mile with 50 inches of precipitation (Price 1962). Within 3 years after the fire, the severe flooding and sedimentation on the 3-Bar Experimental Watershed was controlled to near prefire levels by the vigorous growth of introduced lovegrasses plus some fifty species of native herbaceous cover (Pase and Ingebo 1965).

Conversion of brush to grass may interrupt the erosion cycle associated with wildfire as well as produce one-third to 5 inches more streamflow (Hibbert and others 1974). T.C. Brown and others (1974) estimated that it might be economically feasible to convert about 300,000 acres of National Forest land in the Salt-Verde Basin of Arizona to useful species of grass.

Because of the lesser concentration of population below chaparral watersheds of Arizona than in southern California, flood damage from Arizona Chaparral watersheds is less spectacular but still locally important.

Wetland Forests

Wetland forests generally reflect a dominant influence of an abundant supply of water seasonally or otherwise (Bay and Klawitter 1963). They cover nearly 37 million acres in the southern and southeastern United States, bordering the Atlantic and Gulf coasts and in the lower Mississippi Valley. In the Lake States also, large areas of wetlands are in bogs. Present management there is directed largely to obtain regeneration of forests following harvest (Boelter 1974). Water management is being practiced on more than 2 million acres of wetland forest in the southeastern United States (Klawitter 1972). Although most of this management has increased timber productivity of the land, it may have various hydrologic consequences as well. The primary objective of water management designed to fulfill productivity objectives is to hold sufficient water on some parts of the land to obtain maximum forest growth but in other places to remove surplus water in an orderly manner. Surplus water in headwater bays and wet flat lands is not waste water, for such water is used to recharge swamps in bottom land soils; to maintain water fowl, aquatic, and estuary habitats; and to provide buffer against salt water intrusion. To accomplish these objectives, a water management system must be designed to meet both on-site and the downstream objectives. The design will vary depending on the type of wetland involved. Klawitter (1972) has summarized management objectives and techniques for four types of wetlands: wet flats, bays, swamps and upland ponds, and bottomlands.

Wet Flats

Wet flats are upland sites located on broad, level to nearly level [illegible]erstream areas of the lower coastal plain a[illegible]twood section. Most efforts in water management are now concentrated on the 4 million acres of wet flats that support pine. One current procedure is to remove surface water and lower the ground water enough by means of surface ditches to increase the trafficability for heavy equipment and thereby facilitate road construction and timber harvest. For estimating the effects of drainage on flood flows, Klawitter (1972) suggested that the maximum 24-hour average flow rates can be computed by using the Cyprus Creek formula (Stephens and Mills 1965). He applied this formula to southeastern wetland areas, and arrived at a water removal rate of 1 inch in 24 hours (this is equivalent to 27 $ft^3/sec/mi^2$ of drained area).

Bays

Bays, or upland bogs, cover approximately 3 million acres of wet forest land in the coastal plain. Although they can be found throughout the Southeast, they are mostly in eastern North Carolina or in the northern part of the flatwoods section. Coastal plain bays typically produce relatively little timber, water, forage, and wildlife. Because of fertility problems, Ralston (1965) concluded that not enough is known at this time about the hydro-chemical processes of infertile bay soils to recommend suitable measures to improve forest growth. Numerous stumps have been uncovered where roads or ditches are constructed in this wetland type; this indicates that major vegetation changes have taken place in these areas. Trousdell and Hoover (1955) reported that logging caused water levels to rise enough to endanger regeneration and seriously hamper projected future logging operations. Hydrologic consequences of such changes in the vegetation have not been evaluated.

Swamps and Upland Ponds

Swamps occupy the lowest location along the sluggish streams and rivers in the coastal plain and in the broad depressions in the heads of streams. Occasionally, maritime terraces or sand ridges formed by the sea block areas of low-lying land; these terraces form large swamps like the Dismal Swamp in Virginia, and the Okefenokee Swamp in Georgia and Florida. Upland ponds occupy small depressions in bays, wet flats, or piney woods and are managed in conjunction with them. They are frequently as wet as swamps, but depend on overland flow and seepage from surrounding uplands for their water supply. Swamp vegetation is well adapted to the wet environment: such species as bald cyprus and water tupelo grow best on these sites.

Removal of surface water from swamps can kill older trees and also destroy waterfowl habitat, sanctuaries and escape for deer, and conditions suitable for other wildlife. These values can be enhanced by such methods as installing dikes and control structures at well chosen locations to control the water levels in swamps. Hydrologic consequences of such management have been little studied; however, the characteristics of increased pondage and retention of flood waters would indicate a reduction of flood runoff.

Bottomlands

Bottomlands provide the extra channel capacity required to carry stormflow to the sea. Small streams seldom support a width of more than a few hundred feet, whereas major rivers are frequently separated from adjacent uplands by several miles of bottomlands. Productivity in such bottomlands is high for both timber and wildlife because of the excellent inherent fertility and abundance of moisture in bottomland forest. Uncontrolled drainage adversely affects stand composition, tree growth, and regenerative potential of these lands. Consequently, current water management consists of a kind of flood irrigation—increasing the water available for plant growth by impoundment—construction of low dikes and dams in flats and shallow drainageways (Schlaudt 1962, Broadfoot 1964, 1967). Again, the hydrologic consequences have not been well studied; however, some additional use of water would be expected and some detention benefits of the temporary pondage would reduce flood peaks and prolong water yields in downstream areas. Shallow-water impoundments in bottomlands may attract waterfowl and hence have benefits additional to those of growth and water control. Klawitter (1972) concluded that water management is a means of improving the productivity of millions of acres of wetland forest for wildlife, timber, forage, and water in the southeastern United States. Hydrologic consequences and opportunities associated with the detailed management techniques and wetland conditions need further study.

Phreatophytes

Phreatophytes are trees and shrubs that thrust their roots down to the groundwater under and adjacent to stream channels. Most phreatophytes grow below the forest zone, in desert or plains rather than in a forest environment; for that reason, discussion here is brief. According to one estimate, phreatophytes consume about 25 million acre-feet of water per year in arid and semiarid areas of the West; this is equivalent to about twice the average annual flow of the Colorado River at Lees Ferry, Arizona (Babcock 1968).

On a per-acre basis, phreatophytes consume an estimated 4 to 9 acre-feet of water. How much of this can be "saved" by cutting saltceders, arrowweed, and cottonwood (three chief water users) and how much of the "saving" can be converted to more beneficial use are questions research has not yet answered. In some places this vegetation has enhanced values for recreation and wildlife that have exceeded the estimated value of water that would be saved by removing it.

Horton and Campbell (1974) have summarized some of the possibilities and limitations for management of phreatophytes, and Horton (1973) published a comprehensive abstract bibliography of research related to management of phreatophytes and other riparian vegetation.

Robinson (1967) reported that annual savings in areas of dense growth may amount to 2 to 3 feet of water. The depth of the water table may determine the ultimate management of these areas. If the depth is 4 feet or less, cleared areas can be sown to grass. If it is more than 4 feet, replacement of vegetation is more difficult; farming with irrigation presents no problem, but elsewhere the cleared areas invite wind erosion (Horton 1966).

Rowe reported (1963) that during the first dry season following clearing of streamside vegetation along a channel in the San Dimas Experimental Forest, the clearing saved the equivalent of 14 inches depth of water per acre cleared (Rowe 1963); moreover, streamflow increased chiefly in summer and at the beginning of the soil-wetting period in subsequent seasons, when flow usually was lowest and water was most needed.

In the largest phreatophyte control program yet attempted, one area of 5,300 acres in the Rio Grande Valley was cleared of vegetation (principally saltcedar and mesquite); this saved an estimated 14,000 acre-feet of water annually. In current projects, thousands of acres are being cleared in New Mexico, Arizona, and Texas.

Until recently phreatophytes were almost universally regarded merely as wasters of water. Now their place in the environment is coming to be recognized, and multiple-use planners are assessing the benefits of phreatophytes to fish, wildlife, and aesthetics. For example, Bristow (1968) has estimated that the hunting of whitewing doves on 1 acre of phreatophytes in Arizona can add about $880 per year to the economy of the state.

Surface Mining

Surface mining, chiefly of coal, has increased steadily since Word War II. Until 1965 an estimated 3.2 million acres of land, much of it forest, had been disturbed by surface mining in the United States; an estimated 150,000 acres was disturbed in 1964, and the rate has been increasing since then (U.S. Dep. Inter. 1967). In the West alone more than 21 million acres of commercial quality coal and phosphate areas may be subject to surface mining (Copeland and Packer 1972).

Cutting the forest and disturbing the soil in surface mining has much the same effect on water as other activities already described, but the disturbance is greater—truly extreme—and the effects greater. Surface mining sometimes exposes types of rock that have a high potential for polluting the water in streams and impoundments with acid and other deleterious chemicals.

Reclamation of surface-mined areas has proved extremely difficult. For this reason surface mining has been and continues to be the subject of much controversy and legislation. Reclamation involves both engineering—including the proper placement and grading of spoils, provisions for drainage, and sometimes impoundments for trapping sediment—and establishing vegetation. It is being increasingly recognized that, for successful reclamation, the mining operation must be planned and conducted from the beginning with adequate consideration for reclamation requirements.

Mined areas are often difficult to plant or replant. Fertilizing (usually with nitrogen and phosphorous), liming, and irrigation may be required. Sometimes followup treatments are necessary after initial establishment to insure adequate continued growth.

Where forested areas are mined, the reclamation objective is usually to reestablish forest cover. Forestry has a dual role: (a) establishing trees and shrubs to stabilize the site, control erosion, and improve aesthetics, and (b) returning the land to productive use: timber growing, game habitat, recreational use, or some combination of these uses.

Reclamation research was begun in the 1930's by the U.S. Forest Service in the Central States (Limstrom 1960); now several universities and other Federal and State agencies are also studying the problem. Practical methods for planting trees in the East and Midwest have been developed and guides have been published (Paton and others 1970, Davis 1971).

Increasing attention has been given recently to research on the formidable hydrologic problems that follow strip mining (Curtis 1971a, 1971b, 1972a, 1972b). Maximum sediment concentrations from three watersheds in Appalachia increased from 150 p/m to 46,400, 26,900, and 9,600 p/m, respectively, after these watersheds were strip mined. Peak flows increased by a factor of 3 to 5 after surface mining. On the other hand, water quality from restored strip mine areas in pinyon-juniper land in Arizona was well within EPA criteria; content of nitrate nitrogen in water was less than from the unmined control watershed (Verma and others 1975).

Most surface mining in the United States has been done in the East, but it is proposed for producing coal and other minerals in many states in the West (Copeland and Packer 1972). Revegetation, with trees or other vegetation, is difficult under the relatively harsh soil and climatic conditions widespread in the West.

A large volume of literature on reclamation is accumulating (Frawley 1971, Hutnik and Davis 1973, Cook and others 1974, Johnston 1975). Specific techniques for reclamation have been developed to overcome problems of lack of nutrition, adverse microclimate, inadequate water, and erosion inhibiting establishment of plants. Water supply for establishment has been provided by using water harvesting techniques of laying impervious strips between plantings with wax or polyethelene or by irrigation (Aldon 1975). Shaping the soil surface so as to trap snow to augment the water supply has been suggested (Tabler 1975). Use of artificial barriers to stabilize the surface on steep or highly erodible slopes has been found effective (Heede 1975). Much testing has been done to identify plants suitable for use at specific sites (Cook and others 1974), including use of legumes to improve fertility (Vogel 1973).

IV - POTENTIALS FOR MANAGEMENT

The potentials for management and the pressures for improved management differ widely nationwide. In 1962 the U.S. Department of Agriculture estimated that more than 220 million acres of forest and other woodland in the continental United States needed better management to improve conservation of both soil and water (U.S. Dep. Agric. 1962). Here we first discuss potentials for management in general terms and then focus upon six separate extensive regions, each of which has its distinctive forest-climate relationship.

Our prime concern here is forest management with respect to water: increasing water yield, enhancing the forest's flood control function, increasing its prevention of erosion, and expanding its protection of water quality. The multiple-use manager must, of course, use data relating to all phases of resource use in developing strategy for effective management of the forest.

For specific local forested areas, such as those that directly supply municipal water systems, watershed management considerations may be paramount. On other forested areas, watershed management may receive relatively less emphasis than management to promote or provide other goods and services; these differing relative emphases result from social as well as resource considerations.

Conflicting Objectives

While acknowledging the importance of forestry in helping to solve problems of water yield, floods, and water quality, we must emphasize that forestry provides no cure-all; some management objectives are hydrologically incompatible with others. No single method of managing forested watersheds can improve all aspects of water yield and control. If we want more water, we may sometimes get it when we do not want it, and we may have to make special provisions to keep that extra water from damaging property. If we want water yield delayed for summer irrigation, the delay may sometimes reduce production of waterpower in winter or spring. The purest water generally comes from the least used forest. The objective of flood control is not compatible with achieving the greatest water yield. In some places the conflict over objectives is critical; in others, trivial.

Forest management for water production and control must be coordinated with other water management practices, such as construction and operation of reservoirs and filter plants, weather modification, and water harvesting.

Financial incentives often are the deciding factor in determining individual land owners' objectives and whether they practice watershed management. In the words of Marion Clawson (1972), "Unless or until some means can be devised whereby forest managers can gain financially from watershed management, very few programs aimed at increasing the supply or improving the quality of water from forested watersheds will be undertaken" —at least on most private lands. However, public opinion and legal restraints are beginning to exert strong influence on water management of forest lands (Meier 1975).

Management for Water Yield

Forests cover about one-third of the conterminous United States and mark the areas of greatest precipitation and streamflow *(fig. 1)*. These 650 million acres of forest receive about one-half of the country's total precipitation and yield about three-quarters of its total streamflow. On a unit area basis, forest land receives about twice as much precipitation annually as other land, 45 inches versus 22. Because it receives more water, the forest consumes more water than other areas, 25 inches versus 19. More of the precipitation becomes streamflow—20 inches, or 44 percent, from the forest; 3 inches, or 15 percent, from other lands (Wooldridge and Gessel 1966). Forest regions of the United States coincide closely with areas where average annual precipitation exceeds 20 inches and average annual streamflow exceeds 5 inches. Forests and streamflow are highly correlated, particularly in the West. In the Columbia-North Pacific, California, Great Basin, and Upper and Lower Colorado Regions, more than 90 percent of the streamflow originates in high altitude watersheds that are largely forested and are predominantly in National Forests (Water Resources Council 1968).

Water shortages occur locally throughout the country but are more serious in the West. For example, in four of the six western forest regions, the Water Resources Research Council (1968) rated water shortage a major problem; in seven of eight regions in the East, it was rated a minor problem.

By the year 2020, the annual demand for water produced in forested regions is expected to increase by 30 million acre-feet in the East and by 39 million acre-feet in the West, according to projections by the Water Resources Council (1968) for water source regions that contain most of the forest area.

These demands for water may be met in varied ways (National Academy of Sciences 1971). New sources of water may be made available by such familiar techniques as cloud seeding and desalting of saline water; less well developed, such as augmenting fog drip, creation of artificial ice fields, and deliberate snow avalanching, also have possibilities. Part of the demand for more water may be met by conserving existing sources of water. This may be accomplished by vegetation management, reduction of evaporation from soil water and snow surfaces, and by restoration of water quality by reclaiming wastewater. Further, some water can be made more useful by being transported from areas having excess supply to areas of deficit or by using water where it supplements existing supply. Consideration and comparison of the alternatives strongly suggests that the forest may often be a productive and economical source of more water. But since some increases may produce floods, care must be exercised to insure that increases in water yield are useful rather than damaging.

Management for Maximum Water Yield

Research has shown that water yield from forested areas increases as evaporative losses are reduced; therefore, the maximum possible increases from forest cutting are obtainable by some form of clearcutting. First-year increases following clearcutting range from 1 to about 18 area-inches throughout the country. How long the increases in water yield persist depends on the rate of regrowth, which differs widely among regions and vegetation types.

Most of the increases in water yield that have been measured have been on small experimental watersheds surrounded by large forested areas *(table 8)*. In effect, small watersheds are holes cut into the forest canopy. This means that the microclimate on the clearcut areas is not the same as that on fully open areas. The results of clearcutting an area large enough to function as a completely open area have not been completely evaluated. Some large-scale effects appear to be similar to those on the experimental watersheds. The increased runoff from the 300-square-mile Tillamook Burn is like the result of the clearcutting on the H. J. Andrews Experimental Forest. In the East, the decrease in streamflow associated with regrowth on the Sacandaga Watershed is in accord with results at Hubbard Brook. Clearcutting of large areas is unlikely; however, the hydrologic consequences of management of large open areas may be of interest, for some such area may be considered for restoration of the forest.

Water-Yield Increase Resulting from Multiple Use

The possibilities of managing the forest simultaneously for timber, water, wildlife habitat, and other uses have achieved greater importance in recent years following managerial and legislative recognition of the multiple-use potential of forest lands. To some degree we can now have timber harvest, or other use, and more water, too. To some degree we have had both in the past. Although increases in water yield resulting from past forest cutting were usually not evaluated, they must have been substantial. In about 100 years, the area of commercial forest in the United States was reduced from 828 to 484 million acres. Ninety-two percent of this reduction, 316 million acres, was in the East; it cleared 42 percent of the land in 29 states. Now about 2 percent of the total timber is cut annually.

Although we can expect more attention to water in multiple-use management of public lands in both East and West, the withdrawal of lands for wilderness, parks, scenic rivers, and other such special uses will reduce the possibilities for water management as well as timber harvest.

Management for water yield may deserve major emphasis in snowpack zones, for their yields are high, and they have potentials for affecting the amount, timing, and duration of yield. A snowpack zone is any area that receives 60 inches or more of snowfall annually. The snowpack zone is an important source of streamflow in both the Northeast and the West, but the potential for management to increase water yield is much less in the Northeast. These include parts of Maine, Vermont, New Hampshire, New York, northern Michigan, and high elevations in the 11 Western States—a total of about 240 million square miles, most of which is forested. The snowpack zone comprises a little more than one-third of the nation's total forest area. In New England and New York, streamflow in April and May, the principal snowmelt months, constitutes 35 to 50 percent of the annual yield (Lull and Pierce 1960). In the Colorado Rockies above 9,000 feet, probably about 90 percent of the annual water yield originates from snow (Goodell 1966). The snowpack zone in California, 12 percent of that state's land area, furnishes an estimated 51 percent of its streamflow (Colman 1955).

Noncommercial timber lands both above and below the commercial forest zone, mostly in the West, can also provide sizable and widely distributed areas suitable for water-yield management. Generally these lands are in regions where annual precipitation exceeds 18 inches. Research has indicated that the National Forests, under multiple-use programs, can produce an increase in water yield of 9 million acre-feet annually (U.S. Dep. Agric., For. Serv. 1967b). This increase is said to be compatible with sustained-yield timber management. About 7 million acre-feet of the total would be derived from the commercial forest, about 1 million from phreatophyte clearing, and the remainder from chaparral and other areas. These estimates are for total potential; considering the time required to start such a program, a more practical estimate of what could be achieved in the next 50 years is 3.7 million acre-feet. New techniques could increase yield and speed up applications of management for increased water yield.

These increases in water yield possible under multiple-use management are attainable by clearcutting in suitably designed patterns, encouraging growth of hardwoods rather than conifers, and prohibiting tree planting in riparian areas. Smaller and shorter-lived increases can sometimes be attained by selection and other timber cutting practices. Only effects on water yield are considered here. However, steadily increasing demands for water, timber, and other forest products will inevitably require emphasis on their simultaneous production. Within any area of management, these uses may well be reconciled by economic analyses like those suggested by Gregory (1955), Black (1963), and Brown and others (1974). The proper combination of timber and water production occurs at the point of greatest possible difference between total cost and total revenue. Restraints designed to prevent undesirable effects on the environment will be increasingly imposed.

Cost of Increasing Water Yield

The costs for increasing water yield under multiple-use management are only a fraction of total costs for maximum yield *(table 11)*; they result from required special cutting practices that restrict the volume harvested and require cutting patterns that may add to logging costs. The estimated cost of $25 per acre-foot for maximum yield is equivalent to 8 cents per 1,000 gallons. The cost of water obtained by increasing forest water-yield is about one-fourth to one-half the cost of that obtained by any other current method except cloud seeding, a method not yet fully researched for its effects over large areas.

Table 11–*Costs of additional water obtained by alternative methods*

Method and location	Cost per acre-foot
	Dollars
(1) Forest management by multiple use:	
Western National Forests	1.44
Commercial forest, United States	0.89 to 3.17
(2) Maximum water yield	
Fernow Exp. Forest, W. Va.	20 to 30
(3) Salt water conversion	
Various locations	80 to 160
(4) Water transmission	
From N. California to New Mexico to Los Angeles	45 to 65
(5) Harvesting water from asphalt basin	
Arizona and New Mexico	80 to 160
(6) Cloud seeding	
California	0.40 to 4

Compiled as follows: (1) U.S. Dep. Agric., Forest Serv. 1967b (estimates by Irvin C. Reigner, Ralph C. Maloney, and E. G. Dunford, Aug. 2, 1969, on file, Forest Serv., U.S. Dep. Agric., Washington, D.C.); (2) Lull and Reinhart 1967; (3) Kohout 1969; (4) Patric 1959; (5) Black and Popkin 1967; (6) Kriege 1969.

In some locations water yield can be substantially increased by forest management designed primarily to produce maximum yields of high quality water. This would cost less than other methods that are sometimes deemed practical. Forest watershed management deserves to be considered as an alternative or an adjunct to other methods. It is more flexible than most alternatives; it can be deferred until the time of maximum need; it can be applied to meet even small local needs; and to some extent it is reversible and can be abandoned without difficulty. The value of yield increases through watershed management may, however, depend on available reservoir storage (Hoover 1969). Forest management may be practiced to increase the effectiveness of water production by cloud seeding.

Leaf (1975a) has estimated, for example, that the combination of converting 40 percent of a forest area in central Colorado into openings 5-to-8 tree heights across, plus augmentation of snowfall by 15 percent (by cloud seeding), would double water yield from the treated area.

Management for Flood Reduction

Floods are among the most damaging of all catastrophies. The Water Resources Council (1968) estimate of potential annual damage (in the absence of protective measures) in the United States was $1.7 billion; by 2020 it will be $5 billion.

Flood damages steadily increase. In 1957, the dollar loss was double that of 1936 despite the expenditure during the 1936-57 period of $4 billion in flood prevention activities. Bernstein (1974) reported that a 1973 appraisal gave an estimated $7 billion having been spent for flood control since 1936; yet annual flood losses are about $1.25 billion and are continuing to increase. Increasing losses have been charged to more frequent flooding, the rise in property values, and the greater occupancy of flood-prone lands.

Forests, which occupy the major area of upland watersheds, are directly associated with flood damage in tributary streams. Estimates of the proportion of total flood damage that is incurred in upland watersheds have ranged from 40 percent (U.S. Senate Sel. Comm. Natl. Water Resour. 1960a) to 56 percent (Ford and others 1955).

Forest-flood relations in the East have been discussed in detail by Lull and Reinhart (1972). Floods resulting from late summer or fall hurricane rains strike the East. The most damaging storms in the Northeast were in 1955 and 1972. There were two hurricanes in 1955; rainfall from Hurricane Connie saturated the soil, priming it for the next week's onslaught of Hurricane Diane, which deposited record rainfall in eastern Pennsylvania, New York, and southern New England. In 1972, Hurricane Agnes became stationary over Pennsylvania. It deposited as much as 18 inches of rainfall during the period of June 20 through June 25, and caused the biggest flood ever recorded on the Susquehanna River (Pennsylvania State University 1972). Hurricane Camille in August 1969, which deposited 28 inches of rain in 8 hours, was most damaging in Virginia (Williams and Guy 1973).

In the East, floods from snowmelt alone are rare, but they occasionally occur. The flood in April 1928 in the deep snow country of the western Adirondacks was caused solely by the delayed thaw of a heavy snow cover (Hoyt and Langbein 1955).

In the forested West, precipitation is generally low in summer and high in winter. Exceptions are the frequent short-duration high-intensity summer rainstorms along the front ranges of the Rockies and on the Intermountain Plateau; occasionally there are similar storms over most of the mountainous West that produce damaging flows. In the far West, snowmelt floods occur nearly every year in late spring or early summer in some major basin draining the Rocky, Sierra Nevada, Cascade, or Olympic Mountains.

In the high rainfall zones of California, western Oregon, western Washington, and Idaho, early winter storms are the most frequent flood producers. Rain on low-lying or shallow snowpack produces the greatest floods. Snowmelt floods in the major valleys, usually in June, are second in frequency.

Three types of protective measures can reduce flood peaks or prevent increases in them. In order of increasing opportunity they are: management of existing forest land to reduce floods from rainfall, conversion of open land to forest, and snow management.

Forest Management and Rainfall Floods

Opportunities for moderating floods lie in management of timber, fire, and grazing.

Timber harvesting affects a large portion of the forest at one time or another. Soil disturbance from logging typically occurs on 10 to 40 percent of the area harvested. Extreme disturbance (77 to 88 percent of the logged area) may follow tractor logging and burning slash of old-growth redwood (Boe 1975). Three obvious ways to reduce stormflow are by reducing the disturbed area by choice of yarding method (Rice and others 1972), by rehabilitating logged areas that produce overland flow, and by providing filter strips between bared areas and streams. Keeping soil out of the channel is discussed below under ''Management for Water Quality'': this helps maintain channel capacity and channel bank stability and reduces the bulking of stormflows to a minimum.

Cutting trees reduces evapotranspiration and soil-water storage opportunity in season. Hence, for prevention of dry-mantle floods management of both private and public forests should aim at limiting the area of any sizable drainage that is subjected to heavy cutting at any one time and do whatever is necessary to insure rapid regeneration. It is also beneficial to increase the stocking of trees in some existing stands to increase evapotranspiration and soil-water storage opportunity. The Water Resources Council (1968) has indicated needs for timber stand improvement on 9 million acres of federally owned land and on 20 million acres of non-federally owned land.

Wildfire burns over about 5 million acres of forest in the average year. Reduction of this acreage moderates flood damage, at least where intense fires are prevented or limited in areas that have high flood and sediment potential and slow or incomplete recovery of vegetation after fire. Fuel management (including burning and other measures) is important in prevention of wildfire damage. Besides helping to reduce the acreage damaged by wildfire, fuel management can reduce the impact on those areas where wildfire does occur. Conditions differ widely, even within regions and sometimes from year to year in the same area; however, we have stated some generalizations in various sections of discussing differences in regional fires and flood frequency.

Wildfire may occur infrequently on any area, but grazing is usually an annual harvest. About 85 million acres of forest are grazed. Since an estimated 20 million acres (about 4 percent of the total forest area) is grazed heavily enough to cause overland flow, grazing poses local flood problems but no widespread danger. Good watershed management (and good livestock management, too) must determine the safe carrying capacity of the forest range and then limit use to that capacity by using measures required to effect proper seasonal use and distribution of stock. This means eliminating grazing in some forest areas.

Conversion of Open Land to Forest

Research has amply demonstrated that the conversion of idle, eroding land to forest can sharply reduce peak flows over a period of 10 to 20 years. The dimensions of the job that needs to be done are indicated by the 35 million acres of commercial forest land that are less than 10 percent stocked and may need to be planted (U.S. Dep. Agric., For. Serv. 1965). A more recent estimate indicates that 22 million acres of understocked land need reforestation (Water Resources Council 1968). Even where these lands pose no massive flood threat, their rehabilitation would help to reduce flood peaks on tributary streams and would alleviate sedimentation problems downstream.

Snow Management

If floods from either snowmelt alone or from rainfall plus snowmelt originated on forest land, they are forest-influenced. The patterns in which forest trees are cut or left can influence snow distribution, melt rates, and snowpack influences on storage and delivery of rain (Anderson 1963, 1970a, Hoover 1971, 1973, Smith 1974). Although most forests probably are not managed primarily for flood prevention, the selection of cutting patterns and the scheduling of forest cutting may well be influenced by flood prevention objectives. The options are many, the effectiveness is great, and the objectives complement other objectives, such as water quality control.

Goodell (1959) explained that forest influences together with topographic influences can reduce flood peaks by desynchronization. Topography has the greatest influence on flood peaks. Snow on south-facing slopes characteristically melts earlier than snow on north slopes. Forest management can enhance this desynchronization by increasing the variability of melt rates over a large watershed. If, for example, the forest on a south-facing slope is managed to produce wide open strips running north and south, snowmelt should be seasonally early. If a north slope has dense continuous forest cover, the melt should be comparatively late. Thus, melt water from the south slope should be largely discharged before the north-slope yield reaches its maximum. Complexity arises on large watersheds where consideration must be given to the timing of discharges from numerous slopes differing in steepness, aspect, and elevation. Complexities arise in management for wet years and dry (Anderson and West 1966) and in slope exposure in areas that have different snow amounts or characteristics (Smith 1974, Warren and Ffolliott 1975).

Management for Maintaining Water Quality

Recent Federal and State legislation has given top priority to management for water quality control. Four Congressional acts with five amendments and recent presidential Executive Orders constitute the existing status of water quality legislation for United States surface waters. A particular concern has risen about nonpoint sources of deterioration of water quality, such as might be associated with forest roadbuilding, treatment of logging residue, and preparation of sites for planting (Meier 1975).

Management of the quality of water from forest lands must rely on four basic steps:

1. Appraisal of the present and potential uses of water and how those uses would vary with different characteristics of water quality.
2. Appraisal of the present water supply and characteristics of its quality, including its natural variability.
3. Appraisal of the changes in quality that can be achieved by alternatives in management.
4. Appraisal of the value to beneficial uses of water that could result from alternatives of management.

Uses of water from forest land may be the crucial decision variable in forest land management. A local domestic water supply or local fishing requirement may dictate the direction and stringency of water quality management. On the other hand, the quality of water delivered to a downstream reservoir may seem to be equally crucial to a management decision, but may not be, for a filter plant could be installed to produce suitable improvement in quality. It has been said that "any water of improved purity will find a use", but the forest is there to use also (Lantz 1971b). Let us look at some of the characteristics of water quality supply from forests and then at the effects of management alternatives on water quality characteristics.

The forest has amazing capacity to buffer changes in the water's content of solids, dissolved inorganic chemicals, organic compounds, and microorganisms. Solid particles eroded from the soil surface in local areas may be filtered effectively by the forest floor or the forest soil together with other absorbed materials. The forest floor and forest soil naturally absorb both organic and inorganic chemical compounds; this was dramatically demonstrated by spraying massive quantities of domestic, industrial and agricultural wastewater on forest sites (Sopper and Kardos 1973). Nikolayko (1974) has documented the removal of microorganisms by the filter effects of the forest.

But natural forest systems do not necessarily produce the best quality of water for all uses: organic acids from forest litter may produce water high in calcium content in regions underlain with limestone, phenols dissolved from leaf fall in streams may produce undesirable odor or taste in the water, and water temperatures may be kept too cool for greatest production in the aquatic environment. Streamside vegetation may dry up channels. Local soil and climatic accidents such as landslides may produce occasional deterioration in water quality. At the same time that we consider maintenance of water quality we may consider enhancement.

The parameters of water quality subject to management could be any or all of the more than 40 listed by the Environmental Protection Agency (1972), but the ones currently being monitored from forest lands are generally turbidity, suspended sediment, pH dissolved oxygen, total dissolved solids, and temperature. Other parameters may include coliform bacteria, phosphorus, nitrates, certain heavy metals, and chlorides. The products of erosion contribute directly to several of these parameters and have received the most study.

Erosion and Sedimentation

It has been estimated that 80 percent of the deterioration in water quality is due to suspended sediment, mostly from soil erosion.

Forest cover strongly influences the volume of soil erosion and the influx of erosional products into streams and lakes. Man's activities in the forest often accelerate erosion and sediment production; this has long been recognized, and much has been written about the problem and how to prevent it.

Surface erosion, gully erosion, mass soil movement, channel erosion, and the transport of eroded material all degrade water quality. Suspended sediment damages municipal and industrial water supplies and also causes problems within the forest ecosystem itself. Dirty water degrades the aquatic habitat, reduces recreational use and enjoyment of the forest, and detracts from its visual appeal.

The magnitude of the problem of erosion control on forest lands depends on several considerations: soil disturbance, topography, and the nature of the soils, to name a few; each of these varies widely within any given region.

Basic statistics of the National Inventory of Soil and Water Conservation Needs (U.S Dep. Agric. 1962) show that about 1 percent, or 4.5 million acres, of the forest land in the East needs treatment to control erosion. Almost half of this area is in the Southeast (largely in Alabama, Georgia, and Mississippi), and more than onequarter is in the Central States (mostly Kentucky and Missouri). These estimates indicate that about 9 percent, or 7.5 million acres, of the forested West needs treatment to control erosion. Two-thirds of this area is in the mountainous portions of Arizona and New Mexico; most of the remaining third is divided about evenly between California and Oregon.

The severity of soil disturbance is often the prime factor in soil erosion. It is surely evident by now that an undisturbed forest soil promises a minimum of erosion. With some exceptions, surface erosion, mass movement, or channel cutting may be expected whenever mineral soil is exposed by logging, fire, or grazing.

Erosion Control—Logging

Erosion control begins with planning the road system and its drainage. The design of an erosion control drainage system requires information about the volume of water to be drained, the erosion potential of the subsoil, and the duration of use of the system (Engberg 1963). Since as much as 90 percent of the sediment produced by erosion on timber sale areas comes from roads (Packer and Christensen 1964, Megahan 1975), planning must begin with careful choice of logging methods appropriate to the area and with careful road location and design (Engberg 1963, U.S. Environmental Protection Agency and others 1975). Logging and skidroad mileage can be reduced by logging with skyline systems that reduce soil disturbance by about one-half of tractor logging. New equipment that can traverse roads having steep grades promises to make short access to ridgetop roads feasible, thereby reducing road erosion. In the future, balloon or helicopter logging may reduce soil disturbance even more (see the section on Timber Harvest and Erosion).

Slope-length relationships and frequency of use should govern road location. For example, a 4-percent grade may reduce drainage problems, but an 8-percent grade requires only half the length of road to reach the same elevation and may not tax modern vehicles. The time required for travel would also be shorter (Byrne 1963). Near the end of the road soil disturbance may be reduced by lowering road design standards to meet the expected reduction in road use (Banta 1963). Narrow roads with grades as steep as 20 percent have been used on low-use, dead-end spur ridges in an attempt to stay on the ridgetop and avoid the steep, thin-soiled headwalls and midslope locations. Side casting of road cut material on steep slopes may scour off shallow soils; in southwestern Oregon, end hauling to waste disposal areas has been proposed as a solution to this problem (Dittmer 1971).

In areas having diverse soils, a map of forest soils may be the basis for locating forest roads away from erosion-prone areas (Fisher and Bradshaw 1957). Similarly, identification of slide-prone areas from soil series and slope classes may enable avoidance of these major sources of erosion (Wallis 1963). The effects of road location and construction standards on sedimentation were clearly indicated in a recent study of deposition in reservoirs in 48 northern California watersheds. Streamside roads produced twice as much sediment as roads located on ridges or slopes; the greatest producers of sediment were improved secondary roads at streamside. Deposition increased 6.9 times for each mile of road per square mile of watershed above a reservoir (Anderson 1974). Road location is especially important in steep watersheds (Anderson 1976).

The control of road erosion requires not only proper location but cut and fill-slope protection and drainage necessary to prevent overland flow from developing enough depth and velocity to seriously erode the road surface and roadside ditches; Drainage must also prevent road runoff from reaching the stream channel directly. Surface flow has been diverted to roadside filter areas. Planting ponderosa pine on road fill slopes has effectively reduced surface erosion of fill slopes (Megahan 1974). Erosion from road fills and cut banks has been reduced by seeding, mulching, and fertilizing (Dyrness 1975, Berglund 1976). Mulching the surface is particularly important if erosion is to be prevented the first year after road construction, before vegetation becomes fully established.

But logging is more than roadbuilding. Prospects for maintenance of water quality by prevention of erosion associated with logging involves proper choice of a combination of silvicultural method, logging method, slash disposal, and post-logging treatments that will keep local erosion to a minimum (Rothacher and Lopushinsky 1974). Secondary effects must be controlled: augmentation of water yield, rapidity of snowmelt, and decomposition of forest floor material. Local erosion is being controlled chiefly by dispersion of forest residues, installing crossdrains in skid trails, and seeding bare areas with grass; however, the control of channel erosion induced by the increased water yield or increased rate of snowmelt is only starting to be recognized and properly evaluated. Current evaluations involve selection of selectable increases in water yield associated with the area and type of cutting patterns (Galbraith 1975); then, the channel's tolerance must be appraised separately on the basis of a stability rating. If need be, the area to be logged is adjusted to meet the yield-stability criteria. One appealing prospect is to minimize the impact on the initial reach of the channel by making widespread, numerous small cuts or resorting to single tree selective cutting.

Part of the total problem of logging is disposal of the logging wastes that in steep forest area usually end up in stream channels; this poses another whole set of water quality problems.

Organic debris, which may vary from whole trees to simple organic compounds, poses varied problems to the forest manager. These problems vary from bulking and damming of flood flows to producing offensive odor in drinking water. The primary problems of water quality involve slow mechanical wear of debris in streams, dissolved solids affecting stream chemistry, and dissolved organic substances affecting water taste or odor. Secondary effects of the presence of organic debris in streams include such diverse things as interacting with sediment in the water, causing blocking of streams and scouring of streambanks, blocking of culverts, reducing stream oxygen, and effects on microorganisms in water action on their food chain. Some of these latter, in certain amounts, may be beneficial (Jackson 1975, Triska and Sedell 1975).

Presence of organic debris in streams along the Pacific coast raises special problems because this debris is present in large volumes, partly from natural causes and partly as a result of poorly planned or poorly managed logging operations (Rothacher 1959, Froelich 1971). Burns (1972) emphasized the need to keep all timber out of streams because decaying slash depletes intergravel oxygen. Low production of salmonids in clearcut watersheds of the Olympic Peninsula of Washington has been found to be associated with the large amount of organic debris in the streams (Allee and Smith 1974).

Froelich's outline (1971) of procedures for controlling the gross organic component of debris in streams essentially agrees with all other guides for eliminating pollutants from streams: the best control is simply to keep the pollutant out of the stream. Clearing debris out of channels, particularly channels of narrow streams, may actually cause more damage than leaving the stream alone (Burns 1972). Hewlett and Douglass (1968) found that most of the increase in sediment in streams on a multiple-use water shed resulted from stream "improvement" activity, including clearing. A study of 304 stream reaches in the upper Missouri River basins following the 1948 flood (Anderson and Ingebo (personal observation)) revealed that presence of debris did not reduce stability of first order tributary streams, whereas debris in stream links of higher order streams frequently caused scour of banks by forcing the flow to bypass it. Berry (1975) has concluded that reduction of oxygen in streams along the Oregon and Washington coast was closely related to length of clearcuts and temperature of the streamwater and suggests that cutting practices be modified by manipulating the length of clearcuts and leaving buffer strips instead of removing debris from channels.

Microbiological

A common index of the microbiological pollution in water is the coliform content. Prospects for reducing this index by forest management have been published in the Soviet literature. Drobikov (1973) reported that whereas streamflow from a clearcut area had (in summer) a coli index of 2300 to 9600, under the same conditions the index from selective group cutting was only 230 to 2300. Similar prospects for microbiological reductions may occur with choices of silvicultural methods in the United States in areas that have high summer rainfall.

Erosion Control—Fire

Erosion after severe fire is serious, especially in areas where low rainfall or repeated burning delay natural revegetation.

An extreme example of effects of fire on erosion is in the southern California and Arizona chaparral and has been discussed under that heading. Planting either herbaceous or woody species or both can often prevent some potential damage from erosion and sedimentation. The reforestation of 255,000 acres of the Tillamook

Burn in Oregon is an outstanding example of successful reforestation. Now, 25 years after the start of reforestation of part of the burn, trees are 50 feet high—already high enough for a commercial thinning (Oreg. Dep. For. 1973). The hydrologic consequences of reforestation are documented elsewhere in this paper. It is presumed that reductions in sedimentation were correlated with the reduced peak flows that followed reforestation because concentration of sediment in the watershed varies approximately with the square of the number of inches of streamflow.

Another technique for reducing the effect of wildfires on water quality is to use care in timing of post-fire treatments. For a short time, at least, the watershed is highly susceptible to other disturbance, such as road construction or salvage logging. The adverse erosion effects on the Tillamook Burn may have resulted from the post-burn logging and road building in the area described by Bailey and Poulton (1968). Megahan and Molitor (1975) suggest deferring salvage logging until dead needles dropped from trees can provide a ground cover to protect against erosion.

Regional Characteristics and Possibilities: The East

Regional differences in the relation of the forest to water yield, floods, and water quality result in different practices and possibilities for improvement. To assess these differences, we have divided the country into six major regions, three in the East, three in the West. We suggest certain practices that are based on research results already published and on climatic and streamflow data. These recommendations are not definitive; the selected regions are too diverse and the management objectives for even single watersheds too complex to permit statement of more than general characteristics and recommendations.

The three regions in the East and their characteristics are shown in *fig. 5* and *tables 12* and *13.*

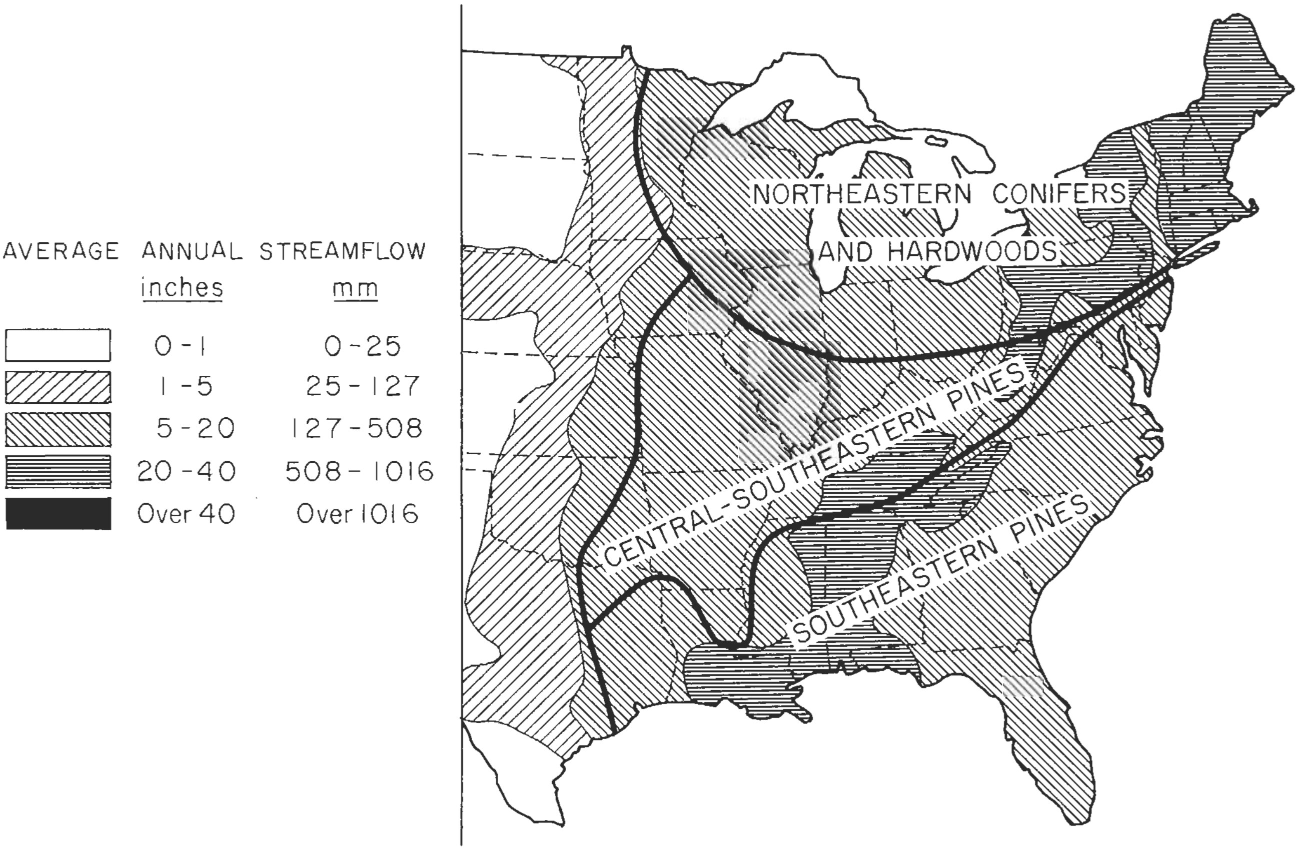

Figure 5—Major forest regions in the Eastern United States, and average annual streamflow.

Table 12—*Mean annual precipitation, streamflow, and evapotranspiration in selected forest types in the East, by geographic regions*

Region and forest type	Area	Mean annual . . .		
		Precipitation	Streamflow	Evapotranspiration
	Thousand acres	*Inches*		
Northeastern Conifers and Hardwoods				
New England, New York, and Pennsylvania:				
White-red-jack pines	5,054	42	22	20
Maple-birch-beech	18,665	39	22	17
Oak-hickory				
Michigan, Wisconsin, and Minnesota:				
White-red-jack pines	4,435	29	10	19
Maple-birch-beech	9,630	30	11	19
Oak-hickory	6,170	30	10	20
Aspen	17,882	28	10	18
Central and Southeastern Hardwoods				
Northwestern portion:				
Maple-birch-beech	3,416	44	19	25
Oak-hickory	61,051	40	16	24
Oak-gum-cypress	10,919	49	17	32
Southeastern portion:				
Oak-hickory	25,776	49	20	29
Oak-gum-cypress	25,884	50	13	37
Southeastern Pines				
Southeastern area:				
Loblolly-shortleaf	52,008	49	16	33
Longleaf-slash	25,967	52	14	38

Source: U.S. Senate Select Committee on Water Resources 1960b.

The East has no areas of perennial water shortage, but occasional droughts cause severe local problems. Other areas have possibilities for increasing water yield enough to meet mounting domestic and industrial demands (Douglass 1974).

Water Chemistry and Temperature

Content of dissolved solids and water temperature are parameters of water quality; management attempts to keep each with certain limits. Dissolved solids content in streams flowing from forested areas are usually low and reflect mostly the local climate and geology. Stream-water temperature, of course, depends mostly on climate; but forest cover may moderate the effects of climatic extremes. Forest treatment can affect both of these characteristics of water quality; they cannot be ignored in forest watershed management, for how we change them can be important.

The principal technique for management for chemical water quality was emphasized by Tarrant (1972): "If you do not want the chemical in stream water, don't put it there!"Chemicals must be kept out of streams and other water bodies, and chemicals should be applied to land surfaces only where the possibility of their movement from land to water is low. The degree to which this has been achieved is stated in sections discussing applications of chemicals for specific purposes.

When timber is harvested, leaving buffer strips of uncut or lightly cut timber is probably the most effective means for preventing undesirable increases in streamwater temperature (Brown and

Table 13—*General characteristics of major forested regions in the East*

Characteristic	Regional forest type		
	Northeastern hardwoods and conifers	Central-southeastern hardwoods	Southeastern pines
(1) Forest area (thousand acres)	98,504	210,240	85,161
Major species	Maple; oak; beech; birch; eastern white, red, and jack pine; spruce	Oak, hickory, ash, maple, yellow-poplar, beech	Shortleaf, loblolly, longleaf, and slash pine
(2) Rainfall, max. 10-year 24-hour (inches)	3 to 5	4 to 10	6 to 10
(3) Freeze-free period, mean length (days)	90 to 150	120 to 330	210 to 330
Snowzone area (thousand acres)	76,740 (78%)		
(4) Flood damage:			
Total mean annual (million dollars)	284	893	419
(dollars/acre, all land)	1.06	1.46	1.41
Upstream mean annual (dollars/acre, all land)	1.57	2.57	3.24

Compiled as follows: (1) U.S. Dep. Agric. Forest Serv. 1965; (2) Hershfield 1961; (3) U.S. Dep. Commer. Environ. Data Serv. 1968; (4) Water Resour. Council 1968.

Krygier 1967). Brown and Brazier (1972) describe a method of designing buffer strips to provide optimum protection for the stream while achieving optimum utilization of timber.

The half of the entire Eastern region that is classed as forest yields roughly 500 million acre-feet of water per year through surface streams alone (Hewlett 1967a). Treating only 10 percent of this area could increase the yield by 10 million acre-feet of water annually, enough to meet the needs of an additional 50 million people. Because they are publicly owned, the 23 million acres of Federal and State forest lands that provide the highest water yields in the East may someday be managed with more emphasis on increasing their water yield.

Northeastern Conifers and Hardwoods

Precipitation in the Northeast ranges from 24 inches in Minnesota to 74 inches in New Hampshire's White Mountains (U.S. Dep. Commer., Environ. Data Serv. 1968). Snowfall averages 60 to 100 inches annually in the Lake States, but rainfall intensities in this region are the lowest in the East. Mean annual streamflow ranges from 5 inches in northern Minnesota to 20 inches or more in much of New England and New York (Busby 1966). The estimated mean annual evapotranspiration showed less spread, from about 18 to 24 inches.

Water yield—Mean annual precipitation, streamflow, and evapotranspiration by major forest types in the Northeast are given in *table 12* along with comparable data for other regions in the East. Streamflow is about twice as great in New England, New York, and Pennsylvania as it is in the Lake States for similar forest types, but evapotranspiration is about the same, around 20 inches.

Water conservation—Water might be saved by not planting trees adjacent to reservoirs, where in essence the plantings would become riparian vegetation; it has been estimated that this could save 1 to 6 inches per year in the Northeast. Herbaceous vegetation, which might be encouraged to promote soil stability in these areas, would consume some of this saving, but not all of it (Lull and Reinhart 1967). Where esthetically acceptable, cutting trees adjacent to reservoirs may save water.

In humid areas, riparian sites near streams may be shaded and cool, with a consequent reduction in the potential for evapotranspiration, or sufficient water may be available for near-potential evapotranspiration over the whole watershed. A riparian cut here would have an effect no greater—possibly not as great—than a cut elsewhere.

Limited evidence from the East suggests that favoring hardwoods rather than planting conifers would increase water yield. Savings might amount to from 2 to 10 inches per year, or perhaps even more. On conifer plantations under intensive management (including periodic thinnings and intermediate and final harvests), the reduction in water yield from pine stands compared with yield from hardwood stands would be partially restored. If both water and timber values are compared, conifer plantations may often be preferable to hardwoods. Indeed, private landowners much prefer conifer stands because they yield cash benefits, but increased water yield brings no such benefits.

Clearcutting hardwoods and providing the minimum ground cover necessary for preserving soil stability may increase water yield by an amount equivalent to about half of the hardwoods' evapotranspiration, an annual increase that might range from 8 to 11 inches. Clearcutting under a sustained yield system that encourages immediate regrowth can increase the first year's water yield by as much as 4 to 14 inches. Clearcutting conifers may give as much as 4 inches' greater yield than cutting hardwoods. These increases diminish rapidly and almost completely disappear in about 10 years. Under an 80-year sawtimber rotation and even-aged management, the net increase in water yield could range from 0.5 to 0.7 inch annually. Of course, this is in comparison with water yield from a forest previously subject to no cutting at all; if the previous yield was affected by prior timber harvest or other forest removal, this increase would be reduced or eliminated.

If timber is taken from a watershed under a cutting system that removes timber uniformly over the entire area and creates only very small openings, there is some evidence that the increase in yield would be no more than about one-third of the increase that could be realized from block cutting the same volume of timber (Lull and Reinhart 1967).

For the northeastern region, Lull and Reinhart (1967) summarized the costs of achieving the maximum water yield that is consistent with maintaining a protective ground cover by removing fully-stocked, noncommercial stands. These costs were $100 to $200 per acre for clearcutting and $10 to $60 per acre for herbicide treatments, controlled burning, or bulldozing to further control vegetation. Combinations of treatments or retreatments might be necessary to establish and maintain the desired cover. The cost in terms of water yield could be an estimated 10 cents per thousand gallons or $33 per acre-foot.

Foremost among the potential management areas would be the 2 million acres of forest land in 14 northeastern States that comprise watersheds and reservoir-protection areas under the control of more than 750 municipalities, private water companies, and State and Federal agencies (Corbett 1970). The principal function of these areas now is to protect water quality; they also provide whatever income can be derived from harvesting forest products without reducing water quality.

Peak flows—The occurrence of highest flows in early spring rather than in winter is a distinguishing characteristic of the northeastern region (Miller and others 1962). The combination of spring rainstorms and snowmelt has produced record peak flows from New England's forested mountains. Peak flows and most of the annual yield usually occur together; 13 of the 23 inches of annual streamflow from northern New England's watersheds come during the spring months (Sopper and Lull 1965). However, occasional fall hurricane storms produce the highest local peak flows.

There is little question that stormflow is higher from cutover forest land, but mostly during the growing season (Lynch and others 1975, Corbett and Heilman 1975, Patric 1973). The few possibilities for reducing flood peaks from forested areas depend on logging practices that require a minimal area of road systems and landings and control overland flow from them. Another possibility is the reforestation of 8.5 million acres of nonstocked forest land. But where high spring temperatures may rapidly melt the snow accumulated under conifer plantations, planting conifers may occasionally serve only to increase peak flow on these occasions. In such areas, a combination of open land (with soil stabilized) and forest land may be preferable. Federer and others (1972) recently reviewed pertinent research, and concluded that the possible effects of snow management on floods in the Northeast are small, that regional management is impossible because of the many ownerships, and that management of forests for protection from snowmelt floods need not be considered further in this region. According to another viewpoint, management should aim to preserve the existing diversity of land use, which serves to desynchronize peak flows from different parts of northeastern watersheds.

Sedimentation—The minimum sediment concentrations in the country are in the northeastern region (Rainwater 1962). Streams draining watersheds that have all types of land use average 280 p/m or less in most of this area, whereas streams in northern Ohio, northern Illinois, and southern Wisconsin average values as high as 2,000 p/m. Mean concentration is estimated at 390 p/m, equivalent at 10 inches of annual streamflow (in the Lake States) to 283 tons per square mile, and at 25 inches (in New England) to 707 tons per square mile. These sediment concentrations are far above acceptable standards for water quality; hence management of forest land to improve or at least not further impair downstream water quality is important.

Erosion on forested lands occurs only on areas where soil has been disturbed. Stony soils and the formation of erosion pavements in most of the region preclude prolonged soil loss. The 10,000-square-mile Driftless Area in southwestern Wisconsin presents the greatest erosion problem because of its highly erodible soils and steep topography.

In all of the Northeast, road design and maintenance are crucial to sediment control (Kochenderfer 1970). Spacing of cross drains and width of protective strips have been determined by the steepness of the road. Trimble (1959) recommended that maximum grades on truck roads or heavily used skidtrails on municipal watersheds should be less than 10 percent, except for very short stretches. Such roads can be drained adequately by cross drains spaced by this rule of thumb: divide 1,000 feet by the percentage road grade. With a 5-percent grade the drains would be 200 feet apart; with a 10-percent grade, they would be 100 feet apart.

The recommended minimum distance from road to stream in the White Mountains of New Hampshire is 50 feet plus 4 feet for each percent slope to the stream. Thus, on a 20-percent slope the road should be located at least 130 feet from the stream (Trimble and Sartz 1957). Water-spreading devices below the drainage outlet could make narrower strips acceptable.

The key to maintenance of good water quality in the northeastern forests, according to Trimble and others (1975), is intelligently regulated roads and application of known good logging practices; otherwise impairment of forest water quality is certain.

Chemical water quality—The study of nutrient discharge after clearcutting in New Hampshire showed concentrations of nitrate and some other ions in streamwater as high as 26 mg/l; this is the highest concentration found after clearcutting anywhere in the country (Hornbeck and others 1975, Pierce and others 1972). In the Fernow Experimental Forest, Aubertin and Patric (1974) reported that increases in nitrate-nitrogen concentrations in streamflow following cutting averaged about 1 mg/l or less. Increases at individual locations had comparable values. Similar results were reported by Lynch and others (1975) in a study in Pennsylvania. When only a small portion of any large drainage in areas like these is clearcut at any one time, nutrient concentrations do not increase enough to be a hazard to drinking water. However, even with this precaution, there might be a problem of local eutrophication, and probably temporary stream and lake eutrophication as well.

Central-Southeastern Hardwoods

The Central-Southeastern hardwoods region, largest of the six forest regions, extends from the 95th meridian across the Mississippi and Appalachians into the Coastal Plain. Mean annual precipitation is as much as 80 inches in part of the Appalachians but only about 36 inches at the western edge of the region; corresponding runoff for these areas is about 40 and 10 inches, respectively. The estimated evapotranspiration ranges from about 26 inches in the northern portion of the region to about 40 inches in northern Louisiana.

Water yield—For the upland types in this region, streamflow averages about 40 percent of precipitation; for the oak-gum-cypress type, the average is about 30 percent (*table 12*).

Clearcutting hardwoods in this region and maintaining a soil-stabilizing ground cover can increase annual water yield an estimated 8 to 14 inches in the northwestern portion and 12 to 16 inches in the southeastern portion; the first year after cutting, the yield may be 3 to 4 inches greater than this. In the southern Appalachians, streamflow increase after cutting is approximately twice as great from north-facing as from south-facing watersheds (Douglass and Swank 1975). If regeneration is immediate, this yield diminishes to a negligible amount through a recession period of 10 to 20 years. Again, under even-aged management, an 80-year rotation, and cutting a portion of each management unit every 10 years, the average annual increase in water yield in the northwestern portion of the region would be an estimated 1.0 to 1.6 inches. Thinnings and selection cuttings would increase water yield a little but only briefly.

The possibility of decreasing water yield from forests in the Southeast is real, if 20 million acres of upland hardwood forests were converted to southern shortleaf pines. Douglass (1974) has estimated that water yield would be reduced 8 inches per year, and that even if the pine forests were intensively managed they would use more water than the present hardwood forest.

Peak flows—In the North Central area, from 12 to 24 percent or more of the precipitation goes into stormflow, but only 4 to 12 percent in the Piedmont and Coastal Plain of the Southeast (Woodruff and Hewlett 1969). Winter is the principal season of high flows. One possible means of flood reduction is reforestation of the 15 million acres of nonstocked land. The present "nonstocked" classification means that these lands do not have silviculturally desirable trees. We do not know how much of it has other volunteer vegetation that serves some useful hydrologic function.

Sedimentation—The mean annual sedimentation rate for this region, coming from lands in all types of use, averages 814 p/m or 944 tons per square mile per year for a streamflow of 16 inches. Streams that drain loessial soils in the Mississippi basin have much higher average rates —as much as 6,000 p/m—and average rates up to 2,000 p/m occur in the Ohio River basin and the Piedmont Zone. Streams in the Appalachians and the Coastal Plain have low average rates, ranging up to about 280 p/m, similar to those in most of the Northeast.

As in other regions, poorly designed and located roads are the main cause of deteriorating water quality (Douglass and Swank 1975). During storms, turbidity is 10 to 20 times greater in a clearcut watershed with logger selected roads than in an undisturbed watershed. In undisturbed watersheds typical storm turbidity ranges from 20 to 30 p/m. However, in a watershed where roads were carefully designed and constructed, maximum turbidity increased tenfold (Douglass 1974). Apparently, in this area it is not enough to just declare that roads are adequately located and designed.

The self-healing process characteristic of northeastern soils is less prevalent in the Southeast; erosion once started on the deeper, less stony soils, continues for longer periods. This places even greater stress on need for careful location, construction, drainage, and maintenance of logging and skidding roads and on the stabilization of road cuts and fill banks. Tree planting has major importance in site rehabilitation and sediment control.

Three opportunities for improvement in water quality in the South through erosion control have been suggested. First, reforestation of 15 million acres of depleted upland hardwoods should reduce erosion. Ursic and Dendy (1965) measured five times greater soil losses from these depleted hardwood forests than from mature pine-hardwood forest. Second, erosion can be reduced during mechanical site preparation for forest planting, which is a chief source of accelerated erosion in the South (McClurkin and Duffy 1975, Dissmeyer 1976). Planting a quick growing cover crop is one method. Third, erosion can be reduced by prevention of overgrazing of the hardwood forests, which is another serious source (Dissmeyer 1976).

Reforestation with pine often takes 10 years to produce a litter cover sufficient to protect the soil. Duffy (1974) combined grass and pine planting; by deferring fertilization, he reduced grass competition with pine sufficiently to allow pine establishment.

Southeastern Pines

The southeastern pine region includes portions of the Piedmont and most of the Coastal Plain. Annual precipitation ranges from 40 inches on the western edge to 60 inches along the Gulf Coast. Rainfall intensities in this region are the highest in the East. The mean annual streamflow ranges from about 10 to 30 inches, and evapotranspiration from about 30 to 40 inches.

Water yield—Mean annual precipitation for both major types of pine (loblolly-shortleaf and longleaf-slash) averages 50 inches, streamflow 15 inches, and evapotranspiration 35 inches (*table 12*). Hewlett (1972) pointed out that although the Coastal Plain areas generally have abundant water, the ridge and valley provinces find water in rather short supply.

Clearcutting southern pine may increase annual water yield by 16 to 18 inches (about half the estimated evapotranspiration) after a protective ground cover develops. The maximum increase the first year may amount to 19 to 22 inches. During regrowth of a forest stand, measurements of soil water suggest that increases in yield may persist for 15 to 20 years and the immediate reduction may not be as sharp as when sprouting hardwoods utilize established root systems. We have already pointed out that even-aged management (an 80-year rotation with parts cut at 10-year intervals) can increase the average annual water yield by 1.4 to 1.6 inches. Likewise, thinnings and selection cutting may be more effective in increasing water yield in pines than in hardwoods (Rogerson 1971). Since pines do not sprout from the stump, reoccupation of the site may therefore be slower.

Douglass (1974) pointed out that although water quality is emerging as a primary problem in the South, water yield management is an important part of quality management.

Peak flows—Winter months (January, February, March) and hurricane months (September and October) are periods of highest flows. Deep, permeable Coastal Plain sands contain and slow the movement of flood-potential rainfalls into streamflow. The Piedmont produces more stormflow, but under the undisturbed forest, the deep soils also hold flood flows to a minimum. Hewlett (1967b) estimated that only 4 percent of the precipitation falling in the Sand Hills and Upper Coastal Plain of Georgia was yielded as stormflow; in the Piedmont it was 10 percent, and in the northwestern Ridge and Valley lands, 15 percent. Several studies have shown that peak flows from eroding idle land can be reduced drastically by establishing deep-rooted vegetation. This appears to be the most effective method of reducing local flood peaks.

Sedimentation—The mean annual sedimentation rate (from all lands in all uses) is about 650 p/m, or 850 tons per square mile for an annual streamflow of 18 inches. The Coastal Plain forest has few sedimentation problems; its most turbid streams average only 280 p/m. The Piedmont is the problem area; some streams there average 2,000 p/m. Logging on Piedmont soils may start erosion that can seriously damage both site and streamflow. With care, however, pine stands on highly erodible soils can be logged without causing serious loss of soil.

Pines are widely used to control erosion. On areas that are not eroding very severely, planted pines can stabilize the soil, develop a forest floor that will facilitate infiltration, and control overland flow in a few years. Where only infertile soils remain, or where ground slopes are steep or eroding badly, seeding for herbaceous cover or mechanical erosion control should accompany or precede pine planting.

Regional Characteristics and Possibilities: The West

Western forests range from semiarid to subhumid. In the semiarid West, the demands of cities, agriculture, and industry for more water from higher-elevation forest areas have generated growing interest and some action programs to increase water yield by forest cutting.

Opportunities appear most favorable on about 15 percent of the area of the 17 states west of the 100th meridian. This 15 percent includes 116 million acres of high-elevation forest land, 22 million acres of chaparral, and 16 million acres of phreatophytes. The maximum possible increase in yield from forest cutting in the West is estimated at 12.5 million acre-feet annually (U.S. Senate Select Committee on National Water Resources 1960b). If we include the potential increase in water yield resulting from clearing of phreatophytes, a goal of 25 million more acre-feet would not appear unrealistic.

The full potential would seldom be achieved. For example, the potential for the lodgepole pine and Englemann spruce-fir types is an estimated 3.8 million acre-feet. According to one assessment, if these types are managed for sawtimber only, with water yields incidental, the increase would be 385,000 acre-feet; if managed for pulpwood, the increase would be 962,500 acre-feet; or if managed principally for water, cutting every 25 years to give an average annual increase of 1.5 inches, the average annual increases would be 1,925,000 acre-feet (U.S. Senate Sel. Comm. on Natl. Water Resour. 1960b). Such increase may now be practical because in these timber types the pattern of cutting that favors water yield is also silviculturally desirable (Leaf and Alexander 1975).

National Forests offer the greatest possibilities for increasing forest water yield. These forests occupy 21 percent of the area of the 11 Western States, receive 32 percent of the precipitation, and produce more than 50 percent of the total streamflow. Their average annual flow is 14 inches, compared to the 3-1/3 inches from areas outside the National Forests. The greatest water producer is the snowpack part of the commercial forest zone, where precipitation ranges from 20 to more than 100 inches annually and much of it becomes streamflow. More than a half million acres of this zone is cut over annually, providing a substantial water increase.

Even in water-short areas of the West, however, management cannot consider water yield alone. Floods are also a problem. History shows that the cumulative effects of burns and reburns on large and small watersheds have posed a constant and widespread flood sedimentation threat. The 100-mile swath across Montana and Idaho left by the 1905 fire and subsequent reburns is still partly unstocked or understocked; the Yacolt fire in Washington and the Tillamook fires in Oregon left huge devasted areas. In all of western Oregon, logging and burning had left only 15 percent of the logged forest "well stocked," according to a detailed survey in 1947 (Anderson 1952). In 1970 the Sky Harbor and 2,000 other fires, started by a single lightning storm, burned more than 200,000 acres in central Washington. In view of the known long-term effects of fire on western watersheds, we must expect hydrologic problems from these recent conflagrations (Anderson 1976b).

Snowmelt and rain-on-snow have produced some of the largest floods in the West. Availability of snow and the frequency and amount of rainfall determine the potential hazard. In western Oregon, for instance, the combination of the two places the greatest potential hazard at elevations between 2,000 and 4,000 feet. This is the zone, therefore, where flood protection is most needed (Anderson and Hobba 1959).

Erosion and its consequences in deteriorating water quality are management problems throughout the West; logging roads and skidtrails must be planned in advance to reduce both length and gradient (Silen and Gratkowski 1953, Mitchell and Trimble 1959). Planning also includes locating cutting areas and landings before logging begins. Landings should be so located as to minimize yarding across streams (Dunford 1962). In the western snow zone, measures to minimize sediment production include patch or contour stripcutting on steep slopes, leaving strips of trees adjacent to the channels of headwater streams, keeping road fills away from streams, revegetating road cuts and fills, diverting road-drainage water away from stream channels, keeping landings out of drainages, diverting water from skidtrails after their use, and removing temporary stream crossings (Anderson 1966). Sedimentation damage from floods in the Pacific Northwest has led to recommendations for intensive planning: "To minimize damage to the forest transportation system, roads and bridges must be planned, designed, constructed, and maintained with adequate recognition of soil stability problems. . ." (Rothacher and Glazebrook 1968). Specific items include retaining walls where necessary to reduce fill embankments, grade dips as a safety measure in case culverts or ditches become blocked, trash racks to reduce culvert plugging, and gabions to minimize bank erosion at stream crossings.

Detailed recommendations for the control of sediment from logging roads have been developed for the Intermountain and northern Rocky Mountain regions (Packer and Christensen 1964, Packer 1967b), for forest and brushland zones in California (Kraebel 1936), and for the Douglas-fir region of the Pacific Northwest (Society of American Foresters 1961, Rothwell 1971, Burroughs and others 1973, U.S. Environmental Protection Agency and others 1975).

The three major forested regions in the West and their characteristics are shown in *fig. 6* and *tables 14* and *15*.

West Coast Forests

The West Coast forest region, the smallest of the six, features the highest annual rainfall, the deepest snowpacks, and the largest trees. The coastal mountain ranges receive the entire range of annual precipitation, 40 to 150 inches (U.S. Dep. Comm. Environ. Data Serv. 1968); most of this precipitation comes as rainfall. Eastward, the main Cascade Range and the Sierra Nevadas have a similar range of precipitation, but most of it comes as snow. Rainfall intensities range from 6

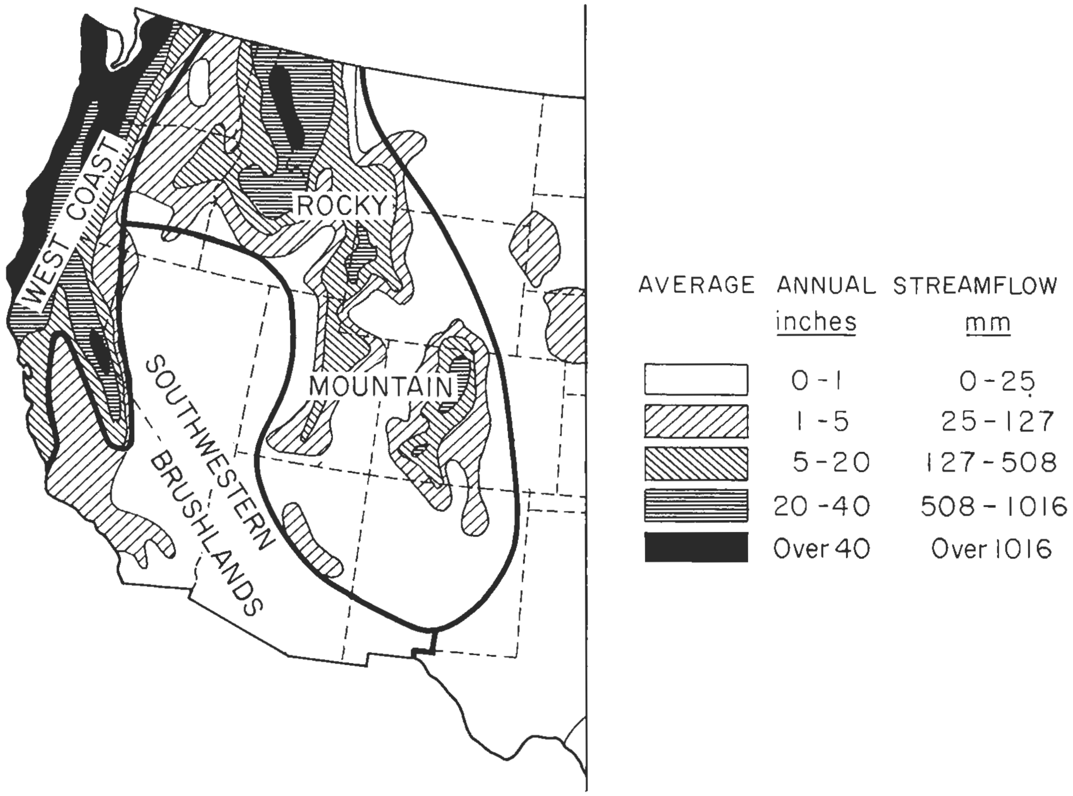

Figure 6—Major forest regions in the Western United States, and average annual streamflow.

Table 14—*Mean annual precipitation, streamflow, evapotranspiration, and potential increase in water yield of selected forest types in the West*

Region and forest type	Area	Mean annual . . . Precipitation	Streamflow	Evapotranspiration	Potential increase in yield
	Thousand acres	*Inches*			
West Coast					
Mixed conifers	8,470	44	22	22	4.5
True fir	6,150	60	36	24	6.0
Douglas-fir, hemlock, redwood	25,570	75	45	30	15.0
Rocky Mountain					
Lodgepole pine	14,470	33	14	19	3.0
Englemann spruce, fir	7,400	33	18	15	3.0
White pine, larch, fir	6,900	42	20	22	4.5
Aspen	4,000	33	10	23	3.0
Ponderosa pine	34,200	21	4	17	0.5
Douglas-fir	9,000	28	7	21	1.0
Southwestern brushland					
Southern California chaparral	7,500	25	5	20	1.0
California woodland, grass	9,000	25	7	18	1.0
Arizona chaparral	5,500	19	1.5	17.5	0.5

Source: U.S. Senate Select Committee on Water Resources 1960b.

Table 15—General characteristics of major forested regions in the West

Characteristic	Regional forest type		
	West-Coast forest	Rocky Mountain forest	Southwestern brushland
(1) Forest area (thousand acres)	36,446	140,818	52,000
Major species	Douglas-fir, western hemlock, redwood, true firs, pines and spruces	Ponderosa, lodgepole, and western white pine; Douglas-fir; true firs; spruces; and aspen	Chaparral, pinyon and juniper, phreatophytes
(2) Rainfall, max. 10-year 24-hour (inches)	2 to 10	2 to 4	2 to 12
(3) Freeze-free period, mean length (days)	90 to 330	30 to 150	90 to 330
Snowzone area (thousand acres)	27,187 (75%)	129,303 (92%)	5,184 (10%)
(4) Flood damage:			
Total mean annual (million dollars)	292	306	222
(dollars/acre, all land)	2.47	0.79	0.94
Upstream mean annual (dollars/acre, all land)	5.19	1.51	2.73

Compiled as follows: (1) U.S. Dep. Agric. For. Serv. 1965; (2) Hershfield 1961; (3) U.S. Dep. Commer. Environ. Data Serv. 1968; (4) Water Resour. Counc. 1968

to 10 inches in 24 hours, at a 10-year frequency along the coast, to 2 to 8 inches on the upland ranges. The snowpack, a principal source of water supply, occupies in season most of the main ranges of the Cascades and the Sierra Nevadas.

In these areas, reservoir storage is a typical way of prolonging delivery of water. Reservoirs become particularly important in forest management for improvement in water supply. Water delayed in delivery from snowpacks can refill reservoirs depleted by earlier withdrawal for irrigation; water saved by manipulating vegetation or a variety of other techniques can replenish reservoirs in dry years or seasons. The basic problem is to make sure that the management applied is compatible with other land uses, water uses, and water control and that the techniques are applied where and when they will be the most effective.

Water yield—Mean annual precipitation, streamflow, evapotranspiration, and potential increase in yield for the western region are given in *table 14*. The potential increase in water yield, based on cutting patterns that would increase the snowpack yield, is equivalent to about one-fourth of the calculated evapotranspiration, or 3 to 6 inches. Studies of the effects of clearcutting in the red fir type in California (Anderson 1969) and the Douglas-fir type in Oregon (Rothacher 1970) have given estimated annual increases of 12 and 18 inches, respectively.

Patch-cutting (with roads) of 30 percent of a watershed in the Douglas-fir type in Oregon increased water yield about 8.5 inches per year over a 5-year period (Rothacher 1970). In the red fir type, first-year water savings estimated at 12, 9, and 6 inches may be derived from strip cuts, block cuts, and selective cuts, respectively (Anderson 1969). Where the objective is maximum snow accumulation and maximum delayed melt, a wall-and-step cutting pattern has evolved. To achieve the pattern in the mixed conifer forest of the California Sierra Nevada the cut strips should be oriented according to topography: Generally, these strips should run east-west on north and south slopes, northeast-southwest on east slopes, and northwest-southeast on west slopes. This arrangement maximizes the shade during that portion of the day when the sun's rays are most nearly normal to the sloping surface. Successive strip cutting, proceeding southward, would then provide a wall of mature trees for shade and would minimize back radiation. The width of strips on south slopes steeper than 20 percent should be about one-half tree height (at rotation age). Strips are spaced according to the number of cutting cycles in a rotation (Anderson 1956). A test of this pattern, where the strip was located so that residual small trees formed the "step," showed a 25-percent increase in snow accumulation. Seventy percent of the increase persisted well into the melt season (Anderson 1963).

Opening the forest in the West has relatively long-lived effects on yields of snow and water; increases probably last 20 or more years. Savings in interception losses may persist to the culmination of the leaf surface on regrowth, about 35 years.

Others areas subject to management for improved water yield include northern California, where there is major opportunity for conversion of brushlands to productive forests, and where water benefits add to the justification. In the high-elevation zones of the Sierra Nevada west-side, for example, 2 million acres of large brushfields could be converted to forest, saving 11 inches of water during the conversion process and ultimately improving management of snowmelt (Anderson 1963).

Peak flows—In the coastal range, highest flows come during the winter months, a result of heavy rainfall on wet-mantle soils. Both the magnitude and frequency of floods appear to be increasing as timber cutting extends through the redwood region (Lee and others 1975). Logging various portions of a watershed on a staggered schedule may possibly change the times of concentration and reduce peaks. Control over the location, design, and maintenance of logging roads, skidtrails, and landing—along with treatment of these areas after use—is necessary to reduce overland flow.

Three types of floods originate in the snowpack zone: from snowmelt, rain on snow, and rain. Rain and rain on snow produce the largest floods. The effects of management on floods depend on the kind of flood and the kind of mangement. By altering the timing of water yield, for example, management may also reduce peak flows (Anderson 1963).

In the Sierra Nevadas of California, for example, periodic snowmelt floods occur as late as June. A dense uncut forest may contribute about 12 inches less water with a much slower melt rate: the snowpack on April 1 may contain the equivalent of 50 inches of water, and melting may continue until the end of June. Large openings, on the other hand, may contain an additional 5 to 10 inches of water, and melting may be enough more rapid that it will cease early in June. The timing of snowmelt in selectively cut areas differs between low and high snowpack years. Because the degree of snychronization of snowmelt from many parts of a watershed determines the size of floods, management practices that augment or diminish such synchronization will increase or reduce snowmelt flood peaks.

According to Anderson (1966), maximum flood protection results from:

a. *Maintaining maximum use of water by vegetation*

   No cutting, selective cutting, strip-cutting on the contour, and other types of cutting, in that order, and maintaining deep-rooted vegetation on deep soils and adjacent to stream channels

b. *Maximizing lengths of water flow paths*

   Maintaining surface infiltration and deep percolation, preventing soil freezing, and draining roads away from stream channels

c. *Maximizing diversity in timing of snowmelt*

   Selective cutting on south-facing slopes coupled with no cutting or strip-cutting on north-facing slopes, and encouraging the formation of snowdrifts with natural or artificial barriers

Sedimentation—Sediment concentrations in rivers differ greatly over most of this region, ranging from 50 to more than 2,000 p/m for watersheds that drain both forest and nonforest lands. In the northern California brushfields, manzanita provides the best soil protection and chamise the poorest. In gently sloping areas, soil is best protected by removing the brush and seeding to grass; erosion rates increase temporarily until the grass is established (Burgy 1958).

The mean annual turbidity (again averaging for all types of land use) is about 54 p/m in western Oregon and 470 in northern California. Average turbidity ranges from 12 to 220 p/m in Oregon and from 8 on the Sierra east-side to 20 on the west-side and as high as 2,000 p/m in north coastal California. In the redwood Douglas-fir forest, excessive disturbance of soils by logging can increase sedimentation eightfold. If revegetation is rapid, sediment concentration decreases rapidly about 3 years after the logging, but large storms may bring back instability and result in further high concentrations of sediment (Fredriksen 1970, Anderson 1970b). Erosion accelerates most on landings, skidtrails, roads, and on the landslides that they may trigger. Proper location, maintenance, and closure of these disturbed areas can reduce sedimentation from these sources to a minimum. However, in unstable stream channels any sources of augmented streamflow—independently of control of erosion at such sources—may be expected to increase sedimentation (Anderson 1975c).

In the Northwest, combination of 25-percent patch cut with slash burning in a watershed with logging roads showed a 6-year average sediment concentration 48 times that on an undisturbed watershed, whereas a complete clearcut without roads had only about a 5-fold increase. Six-year average concentrations of sediment were 9, 48, and 430 p/m respectively in the unlogged, clearcut and patchcut with roads (Fredriksen 1973). Maximum 1-day concentrations showed about equal proportions: 220, 1,000, and more than 10,000 p/m. Fredriksen concluded that practices that reduce soil disturbance by logging or slash burning should be encouraged; these favor rapid regrowth of vegetation and reduce deleterious impacts on water quality in forests that receive heavy rainfall.

Erosion is a lesser problem in the snowpack zones in most years because the snowpack protects the soil from the impact of rainfall, and melting snow seldom generates overland flow. After the snowpack disappears, the principal sources of sediment are areas bared by logging, land slippages associated with logging, road cuts, and burned areas. Heavy grazing may cause small increases in sediment production. Procedures for controlling erosion from logging have already been described; emergency contour trenches have controlled overland flow and sediment discharge from burned watersheds during short, high-intensity rains (Copeland and Croft 1962). C.H. Gleason, in a personal communication about 1963, reported that, as in southern California, trenches sometimes failed when flows from winter rain exceeded their surface storage capacity. Periodically rainstorms at high elevations find little or no snow, and local erosion can be high in such snow zones (Anderson 1963), for soils in these high elevation zones are less resistant to erosion (Willen 1965).

Landslides—In the Pacific Northwest, where roads, and to a lesser extent logging, are responsible for accelerated mass soil movements, landslides can be reduced by locating roads so as to avoid unstable soils and landforms (Fisher and Bradshaw 1957, Wallis 1963, Rothwell 1971, Burroughs and others 1973), by using skyline, or possibly balloon logging in steep, mountainous terrain, and by adjusting streamflow increases so as not to exceed channel capacities. Adequate road drainage and avoidance of sidecasting on steep slopes also reduces the hazard of mass movement (Dyrness 1967a). Landslides have also resulted from the conversion of brushlands to grassland range in California (see the section, "Type Conversion"). Landslides occur sporadically even in undisturbed steep forest lands. Swanston (1969, 1974) and Rice and Krammes (1971) have summarized the nature of mass movement problems in forest lands, some methods of evaluation, and possible management techniques.

Rocky Mountain Forests

The Rocky Mountain forest area (*fig. 1*) extends nearly the whole length of the western United States from central Arizona and New Mexico in the south to beyond the Canadian border to the north. A dozen major types of forest contribute to streamflow from river systems from the Columbia to the Rio Grande and thus are the principal source of water for irrigation of semiarid lands and power developments for the whole West. Something of the vegetation types and general forest hydrology have been described recently in a series of papers. Hibbert and others (1974) have described the south chapparal zone, and Clary (1975) has described the pinyon-juniper zone. H.E. Brown and others (1974) and Baker (1975) have outlined the prospects for water yield from the ponderosa pine forests of Arizona in relation to other multiple-use objectives. Rich and Thompson (1974) have outlined opportunities for increasing water yield in the mixed coniferous zone of Arizona. Overall prospects for increases in water yield in Arizona have been estimated by Ffolliott and Thorud (1975). Leaf (1975a) has summarized the opportunities for watershed management in the principal vegetation types of the central and southern Rocky Mountains. More detail was given by Martinelli (1975) for the Alpine zone; by Hoover (1973) and Leaf (1975b) for the subalpine zone; by Gary (1975) for the ponderosa pine zone of the Colorado front range; by Orr (1975) for the ponderosa pine and white spruce forests of the Black Hills; and by Sturges (1975) for big sage country. Copeland (1969) summarized the possibilities for water management for the coniferous forests of the northern Rocky Mountains.

Water yield—The opportunities for management for water yield in several of the vegetation types of the Rocky Mountains are unusual. Nowhere would the projected use be greater if the demand could be met (Cochran 1974). Demands for water are for energy production, coal gasification, for retrieval of oil from shale, for rehabilitation of mining waste sites, and for maintenance of aquatic habitat. Nowhere is there more compatibility between water management and management of other resources. Since timber regrowth is slow, water yield increases with timber cutting and lasts 3 to 5 times as long as in other areas (Hoover 1973); brushland may be converted to more profitable grassland with a saving in water (Brown and others 1974); alpine snowfields may be manipulated to yield prolonged flow in summer (Martinelli 1975); the vast area (196 million acres) of big sagebrush could be cleared to produce extra water (Sturges 1975), and use of water by phreatophytes and riparian vegetation along streams could be salvaged (Horton and Campbell 1974). Conventional silvicultural practices seem to be compatible with water yield objectives; in addition, evaporation suppression, melt retardation, creation of artificial glaciers, water harvesting from impervious areas, and cloud seeding may be used to increase water yield.

An increased water yield of 3 to 4 inches can be obtained from the subalpine coniferous forest by removing 30 to 50 percent of the total stand in small, well distributed patches. These patches should be less than eight tree heights in diameter; uncut groups of similar size should be left standing for maximum efficiency (Hoover 1973).

The persistence of increases in water yield following cutting of lodgepole pine was indicated by measurements of water yield following the cutting in Fool Creek Experimental Forest. The trend line of expected increase (Leaf 1975b, *figure 11*) indicates an initial increase (in 1956) of 4.5 inches and subsequent decline of increases at the rate of 0.1 inch per year for the 17 years of record. If this trend persisted for 45 years, there would be a possible total increase of 101 inches, or 8.4 acre-feet of additional water per acre of the managed forest.

Less is known about possibilities for improving water yields from aspen forest. Soil-water studies to date suggest that replacing aspens with shallow-rooted vegetation would increase yield where soil depths exceed 4 feet (Brown and Thompson 1965). Cutting openings will increase snow storage in the opened area by one-third (Swanson 1973).

Although not part of the Rocky Mountains proper, the Uinta Mountains of northeastern Utah may afford similar opportunties for mangement for water yield. The area has about 563,000 acres of lodgepole pine forest. Johnston (1975) reported that clearcutting of lodgepole pine resulted in some 4 inches of water remaining in the soil at the end of summer, water "available for streamflow."

Below the subalpine zone in the Rockies lie the ponderosa pine and Douglas-fir forests. Ponderosa pine grows on south and west slopes at elevations of 3,000 to 5,500 feet in the northern Rockies above the sagebrush type, and at 5,500 to 8,500 feet in the Southwest above the chaparral and pinoyn-juniper types. Douglas-fir predominates on the cool, moist north and east slopes, and on south slopes at the upper edge of the ponderosa pine zone. Ponderosa pine covers 34 million acres and Douglas-fir 9 million acres. Average annual precipitation ranges between 21 to 28 inches; the average water yield is 4 inches from ponderosa pine forest and 7 inches from Douglas-fir. Small increases in water yield (0.5 to 1.0 inch) are attainable on deeper soils by harvest cutting but somewhat more from strip and block cutting (Brown 1971, Rich 1972, Rich and Thompson 1974, H.E. Brown and others 1974, Gary 1975). Irregular patch cutting has been recommended for cutting in the ponderosa pine forests in the Black Hills (Orr 1975).

At elevations between 4,500 and 8,000 feet scattered over 43 million acres in the 4-corners states and Nevada is the pinyon-juniper type. Present prospects for treatment of this type to increase water yield are limited by adverse environmental considerations of the known techniques (Clary 1975).

At the lower elevations below the pine and juniper stands there are about 169 million acres of big sagebrush that are susceptible to special techniques for improving water yield (Sturges 1975). Much of this area, particularly in Wyoming, is characterized by periods of drifting snow, and techniques for saving water from this source have been perfected (Tabler 1975). Rechard (1973) has estimated that in Wyoming alone some 2 1/4 million acre feet of water could be saved annually — 1 1/4 million by use of snow fencing and another million by spraying sagebrush.

The best prospects for substantially increasing water yield in dryer areas are by confining or extending clearcutting to streamside areas of supposedly high water use. Relatively large increases can be obtained from the riparian zone, provided evapotranspiration is much higher there than on the rest of the watershed; e.g., where trees and shrubs line water-courses and are exposed to bountiful energy advected from surrounding open or brush-covered terrain. This condition is exemplified by the phreatophyte areas of the arid and semiarid West. After describing the many types of riparian conditions, Horton and Campbell (1974) have concluded that despite this wide diversity, "Only rarely in the Southwest are there phreatophyte areas that would be best managed by complete preservation.'' Vegetation zones in arid land often are susceptible to adverse effects of treatments on sedimentation; special precautions may be needed in managing these zones.

Peak flows—Spring floods that originate from melting snow in the forested snow zone are normally a minor problem in the Rocky Mountains. Occasionally major upslope or convective storms dump large quantities of rain during May and June in the foothills below the snow zone. The normal high runoff from spring snowmelt can aggravate the flooding from such storms. Good cutting practices and the exploitation of topographic influences for protection can reduce peaks by prevention of overland flow and desynchronizing snowmelt (Goodell 1959).

An example of delayed melt was studied in northern New Mexico. Surveys of snowpack conditions there have suggested that at elevations near 9,900 feet, management to delay melting should favor Douglas-fir over aspen. At elevations near 11,150 feet, management to delay melting should favor spruce-fir cover and limit cutting in old growth stands, particularly on south-facing slopes (Gary and Coltharp 1967).

At lower elevations, especially along foothills below 8,000 feet, cloudburst floods are common in the summer months. The greatest floods occur when high-intensity storms strike watersheds after ponderosa pine forests or shrub cover has been burned or severely overgrazed; therefore, protection from fire and overgrazing is important in forest mangement there.

Sedimentation—The mean annual sedimentation rate for the Rocky Mountain area is 7,000 p/m, or 1,100 tons per square mile at 2.25 inches streamflow. Most of the forest region, however, has a maximum rate of 280 p/m, the same as the preponderance of forest areas in other regions.

The snowpack forest produces little sediment in the central Rockies. Snowmelt seeps directly into the soil without eroding it; therefore, streams usually are clear at high elevations. In the northern Rockies periodic rain or rain on snow can produce high volumes of sediment. To keep erosion from logging to the minimum requires preplanning the road system, patch or contour strip cutting on steep slopes, supervision of logging, revegetation of road cuts and fills, careful location of landings, and postlogging care (Noble 1961, Megahan and Kidd 1972, Megahan 1975).

Erosion can be severe at lower elevations wherever soil is exposed by logging or fire. Nearly all the soils in this region are highly erodible. High-intensity rainfalls have produced major debris flows. Much of the sediment is torn from gullies and channel banks. Contour trenching has been used successfully along Utah's Wasatch Plateau to contain overland flows that formerly generated mud-rock flows. Seeding perennial grasses on a burned-over ponderosa pine area in Arizona immediately after fire stabilized the area (Rich 1962). Prevention of fire and avoidance of severe logging disturbance are, of course, more effective in controlling erosion than corrective measures applied later. In the Front Range, improved logging practices and methods of gully control are needed (Heede 1975, Gary 1975); in the northern Rocky Mountains, controlling erosion from roads is the current major problem (Megahan 1974), and control of water quality and esthetics associated with mining are growing concerns (Johnston and others 1975, Jensen 1975).

Southwestern Brushlands

There are 22 million acres of chaparral and woodland in the Southwest, 15 million acres of pinyon-juniper, and 15 million acres of riparian vegetation or phreatophytes that have little commercial value but considerable significance for recreation and watershed use. Mean annual precipitation ranges between 8 inches at lower elevations and 16 inches at higher ones. Maximum rainfall intensities are high, but their frequency is low; 24-hour rainfall at a 10-year frequency ranges from 1.5 to 4.0 inches for most of the region and up to 12 inches in southern California. The mean annual streamflow for large watersheds is only 0.5 to 2.5 inches, the lowest of the six regions. The potential for management of the seven major vegetation zones in Arizona has been reviewed and summarized by Ffolliott and Thorud (1975).

Water yield—Water yield from chaparral may be increased by clearcutting, burning or treating with herbicide, then replacing the chaparral with grass. The lack of protection by natural ground cover requires the substitution of vegetation to prevent excess erosion. Though regional potential increases are estimated to be only 1 inch or less (*table 14*), recent studies suggest possibility of much greater returns on some areas: for example, 3 to 14 inches in Arizona, depending on annual rainfall (Rich and Thompson 1974); 3 inches for grass-covered areas in southern California (Bentley 1967).

High values for water make high conversion costs justifiable. If annual water yield is increased by 3 inches, with water valued at $50 per acre-foot and with low annual operating costs, an initial cost of more than $100 per acre for converting California chaparral to grass would be justified. Typical costs per acre for converting chaparral to grass range roughly between a minimum of $25 per acre and a maximum of $80 (Bentley 1967).

Costs have been somewhat lower in Arizona. Prescribed burning of 3,000 acres of chaparral on the Tonto National Forest in Arizona cost $10 per acre with subsequent herbicide spraying at $20 per acre. The increase in water yield (1.6 inches), increased forage growth, and reduced fire hazard had an estimated total value over a 10-year period of $97 per acre, or a benefit-cost ratio of about 3 to 1. The estimated value of forage, $60 per acre, was about twice the total cost, $30 per acre (Suhr 1967). A 1974 analysis of the economics of conversion of 104,000 acres in the Salt-Verde Basin in Arizona (T.C. Brown and others 1974) indicated an expected increase in basin runoff of 2.5 percent, in cattle carrying capacity by 3.6 percent, and a decrease in fire-fighting costs by 3 percent, for a net annual return of $2.51 per converted acre.

Both in southern California and in Arizona the area covered by chaparral that is suitable for conversion to grass is limited by shallow soils and steep sloping land. Bentley (1961) estimated 9 percent for the San Gabriel Mountain chaparral; T.C. Brown (1974) estimated 21 percent of Arizona chaparral was suitable.

Peak flows—Floods are a major problem in the chaparral of southern California, where fires have often triggered disastrous, debris-laden discharges. The flood threat persists until cover is reestablished, and peak flows remain greater for 10 years or more after a fire. Complete recovery of plant cover may take 40 years.

Flood control is tied closely to fire control, which should include, where possible, the conversion of highly inflammable chaparral to a grass cover or to a less flammable condition by reducing its age and favoring more fire-resistant species. Typically, these measures are effective where the flood potential is low; elsewhere, mechanical control by debris dams and channelizing is needed for control of flood waters and the entrained sediments.

Sedimentation—The mean annual sedimentation rate is 6,400 p/m or 2,300 tons per square mile with a runoff of 5 inches.

Burning brushlands in southern California increases sedimentation enormously, but fire control alone will not prevent it. For instance, Anderson (1949b) estimated that average annual sedimentation was 600 to 9,970 cubic yards per square mile with a then-current annual burn of 0.6 to 3.2 percent; after a proposed fire control program reduced annual burns to 0.2 percent, he estimated the sediment yield would range from 516 to 8,280 cubic yards per square mile.

There seems to be no successful method for stopping erosion after wildfire in southern California. The several methods that have been tried (see "Southern California and Arizona Chaparral") are either limited in effectiveness or are quite expensive.

Success has been reported in Arizona, where mechanical erosion control was combined with seeding of lovegrasses on four small watersheds from which chaparral had been grubbed and used as a mulch; this process reduced sediment rates from untreated chaparral of about 2,000 to 5,000 tons per square mile per year to 16 to 31 tons (Rich 1961). Conversion of chaparral to grass on slopes steeper than 60 percent or on especially unstable soils is not recommended (Hibbert and others 1974).

Erosion control has been more successful in northern and central California than in southern California. Seeding grasses on three burned-over chaparral watersheds reduced erosion rates per acre from 2.2 to 1.1 ton, from 1.7 to 0.5 ton, and from 1.5 to 0.4 ton—less than the erosion from the original chaparral cover (Burgy 1958). As in the southern California conversion, some of these areas subsequently have been subject to severe slope instability, indicated by massive land slides.[11] Steep forest and brushlands that have been converted to grass were found to be a principal source of increased sedmimentation (Wallis and Anderson 1965).

V - TOMORROW'S FORESTRY AND WATER

The study of forestry and its effects on water yield, floods, and water quality has led to three convictions:

1. Substantial increases in water yield are attainable by creating openings in forests
2. The undisturbed forest provides the maximum storage for flood-producing precipitation and the maximum soil stability
3. With care in logging, timber can be harvested from many forests without unduly increasing sediment in streams, water temperature, and water chemical content.

Tomorrow presumably will see these general convictions translated, as necesary, into forest operations as one means of meeting society's demands for water, sufficient in amount and of required quality, with minimum damage in delivery. However, implementing of these ideas will not exhaust the potential of forestry to control water: current research points toward other interesting possibilities.

Water Yield

Now that increased water yield resulting from forest cutting has been achieved and demonstrated at many places, refinements of research are in order to answer such questions as: Where and by what techniques will cutting produce the greatest or most economical yield of water? Can antitranspirants be used to provide seasonal increases without cutting? How does water yield interact with management for recreation? What is the most effective role of the forest in providing needed increases in water yield? This last question also involves comparative costs and benefits.

Selection of Areas for Cutting

Maximum increase in water yield will result from cutting trees or removing brush that transpires at or near maximum rates and durations. Therefore, favorable locations are areas that have deep soil, riparian zones where vegetation has access to groundwater, areas that have direct drainage to channels (treat slopes adjacent to channels, or cut strips perpendicular to contours), and areas where streamflow per unit of precipitation is least (dense forest, sites that receive the most heat energy, and sites subject to frequent drying). A caution: losses from direct evaporation are likely to be high on exposed south-facing slopes and may partially offset reductions in transpiration when openings in the forest are created there.

Hewlett (1961) demonstrated that the base flow of Coweeta's mountain watersheds derives from soil-water drainage; this suggests that cutting trees at the base of slopes produces more water than removing trees higher on slopes (Lynch and others 1974).

Maximum delay in yield will result from accumulating snow in shaded places and at higher elevations, perhaps by using snow fences (Martinelli 1973) and by lengthening water-flow paths as much as possible.

Antitranspirants and Antievaporants

The possibilities of spraying chemicals on the forest canopy to reduce transpiration (and thereby increase streamflow) by forming a film over the leaves, by increasing their reflectivity, or by closing stomata have recently been studied. No great success has been reported. A first estimate was that evaporation from a closed canopy could be reduced by about one-sixth by cutting the width of stomata in half (Waggoner and Zelitch 1965). Later, reductions up to 15 percent in annual

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[11] R. H. Burgy and Z. G. Parazifirou. 1971. Effect of vegetation management on slope stability. (Unpublished report on file, Dep. Water Sci., Univ. Calif., Davis.)

evapotranspiration were found with jack pine grown in lysimeters and sprayed with phenylmercuric acetate (Waggoner 1967). However, since mercury compounds, such as the one applied by Waggoner, pose a serious environmental problem, they cannot be used over large areas. Spraying 70 acres of hardwoods at the Coweeta Hydrologic Laboratory proved dissappointing: streamflow did not increase, apparently because the spray did not reach the stomata-bearing undersides of the leaves. Spraying aspen in Utah produced a better coverage of spray so that the width of the stomata and velocity of sap were reduced by about half; however, this spraying saved only about 1/2 inch of soil water (Hart and others 1969). Spraying red pine plantations in Connecticut saved more than 1 inch of soil moisture (Turner 1968). Anderson and Krieth (1975) report a 50 percent reduction of transpiration by using film-forming commercial antitranspirants; plants showed no apparent injury.

Davenport and others (1969), in reviewing the potential of antitranspirants, noted that they would be most effective when resistance to the passage of water from roots to leaf surface is minimal, when stomata-bearing surfaces are well covered, when new foliar growth following treatment is minimal, and when optimum rates of concentration and application are used. If and when successful antitranspirants are developed and these conditions met, this treatment, combined with cloud seeding, could increase runoff by more than the sum of the increases from the separate treatments (Satterlund 1969).

Antievaporants have been applied to the soil under forest vegetation to reduce summer losses of soil-water. The results of different trials have differed widely. In contrast, the application of antievaporants to snow surfaces has been consistently effective. In the first tests of the use of hexadecanol on brushfields and red fir forests in California, the only significant reductions in the next summer's evapotranspiration were in the bulldozed brushfields and in areas where there had been heavy applications under snow (680 pounds per acre). However, evaporation from snow was reduced by the application of hexadecanol (12 pounds per acre) to the snow surface (Anderson and others 1963). One application may be enough to last throughout the spring melt season (Smith and Halverson 1971). This treatment indicated possible saving of nearly 2 inches of water from open areas in the forest.

Recreation Use and Environmental Quality

Recreational use and environmental quality of forests are receiving progressively increased attention. Recognition of their importance will dictate modifications in forest management for water yield as well as for other purposes. The effects of management practices on water quality, visual appeal, fish and wildlife, and habitat, and other values must be considered and evaluated. Allee and Smith (1974) have graphically reported devastating results to stream environment in the Olympic Peninsula when forest management operations failed to consider these associated values adequately.

Cutting practices will increasingly be modified to leave forests that are pleasing to the eye as well as effective in producing timber and water (Litton 1968, Baker 1975). Setting aside special areas for wilderness, scenic river, wild areas, parks, and historic sites (as well as providing more areas for normal camping, picnicking, and hiking) will make special demands on water supply and pose new problems in water quality. Special treatments of forests may be required to satisfy the objectives of forest recreation.

Comparison with Alternatives

There is no question that water yield can be increased substantially by clearcutting selected forest areas or that the cost of this added water is less than that of other methods now deemed practical. Producing water by managing vegetation costs less than distilling sea water, transmitting water, or harvesting water. And the energy required to convert salt water and to pump water in transmission projects may reduce the feasibility of these alternatives as concern over limited energy supplies increases.

Cloud seeding may prove to be the cheapest source of additional water wherever it is successful. Kriege (1969) reported a 13-percent increase in annual rainfall over 12 years in the Santa Clara Valley of California, at a cost of less than 40 cents per acre-foot ($4 per acre-foot if one estimates that only 10 percent of the increase is salvageable). Hurley (1968) estimated that a $25 million cloud-seeding research program would make it possible to increase winter precipitation over the Upper Colorado Basin by 15 percent by the mid-1970's at a cost of water increases of $1.00 to $1.50 per acre-foot.

Cloud seeding over forested watersheds that have been cut to increase water yield may produce more water than the sum of the increases obtained by the two methods used independently (Satterlund 1969, Leaf 1975b). Cloud seeding and forestry are also related in another way: Cooper and Jolly (1970) have reviewed the possible ecological effects on forests of weather modification, and Ives and others (1970) have discussed programs to evaluate the environmental impacts of cloud seeding in the Upper Colorado Basin forests.

Potential Role of the Forest

The Water Resources Council (1968) has predicted that by the year 2020 consumptive use of water in the East will have increased by about 30 million acre-feet annually, and in the West by 40 million. Potential increases of water yield from forest land could satisfy perhaps one-half or more of these increased needs.

Planning reservoir design and operation together with treatment of forest land to increase water yield can make both more effective (Hawkins 1969); the amount can be increased and the quality of water improved.

Timber harvest designed to increase water yield seems to offer a comparatively economical means for producing at least part of the volume of water needed to satisfy increasing demands.

Drought periods provide special opportunities for forest management for water yield. Where water in the soil may be saved by removing vegetation, the planned conversion of brushfields to forest might well be timed to coincide with critical drought periods; in this way, the saving in water incidental to brush removal might help to offset costs of reforestation. The temporal and spatial sequence of conversion might thus achieve maximum returns for the present and create future forests to meet both timber and water-yield objectives (Anderson 1966). The extension of forests into some areas now occupied by alpine flora may be feasible by techniques that were developed for the Alps (Aulitzky 1967). The use of trees to shade artificial glaciers or deliberately avalanched snow accumulations may make these techniques more effective in prolonging low season streamflow (National Academy of Sciences 1971). Martinelli (1973 and 1975) has discussed use of snow fences and other techniques to prolong water yield in alpine areas.

Flood Prevention

Tomorrow's forestry may contribute to flood prevention in three ways: 1) by acknowledging the flood-preventing role of the forest, 2) by enhancing that role by protection and reforestation, and 3) by pursuing imaginative research to strengthen this role.

Forest Role

Foresters should accept the forest as the best natural cover for preventing floods when it is protected from overgrazing, severe fire, or by denudation by insects or disease. Present-day fire control and restriction of grazing pretty well assure that most forest areas meet flood prevention criteria fairly well except the chaparral of the Southwest, with its peculiar climate and unusually high fire hazard. Certainly the recent extremely large fires in the Pacific Northwest are cause for concern also.

The forest can prevent excessive acceleration of floods under sustained-yield timber management. Flood-producing rainstorms, overland flow, and streamflow are controlled about equally well by sapling, pole, and sawtimber stands. One important key to flood prevention is continued maintenance of an undisturbed forest floor over most of the area. Where disturbance is necessary to enable forest harvesting, it should be held to a minimum; and overland flow should be controlled by proper location, construction, and maintenance of roads, trails, and landings, and by special techniques designed to offset adverse effects. Where snowmelt contributes to floods, special techniques can hold flood-water discharges from watersheds to a minimum.

Protection and Reforestation

The forester's flood-prevention function is twofold: protection and reforestation. Protection from fire, overgrazing, and destructive logging is closely associated with timber production and recreational use as well as with water production. No further justification of protection is required. We reiterate that the occasional, superficial ground fire has little effect on forest soil and water; only repeated fires or high-intensity fires that completely consume the forest floor will damage it seriously. Grazing is another matter; relying on the forest alone as a source of forage can destroy both feed and feeder. Further care in logging, especially in the location and design of logging roads, will be required in future forest protection.

Perhaps the most productive action in forest flood prevention and control is the afforestation of idle, abandoned lands that are sources of overland flow and sediment. Of the 35 million acres of unused plantable land, top priority in forestation should be given to those unforested areas that are truly sources of present or future flood and sediment damages. The nature and expected extent of such damages need to be better assessed.

Research

Research to devise practices that will improve flood prevention should be centered on the three major components of forest floods: local surface flow, subsurface flow, and snowmelt. The first involves control of runoff from such impervious surfaces as roads, landings, and skid trails. The second involves determining the possibility of slowing down subsurface flow by temporary storage, utilizing incompletely filled soil-detention storage, or by developing access to underground storage beneath subsurface flow planes. Capitalizing on this available storage capacity may involve combining surface forest with subsoiling, using explosives underground, or digging wells. No systematic research on soil engineering for modifying soil-water storage has been reported, but such research was recommended in a National Academy of Sciences (1971) report. Discovery and use of those strategic areas that can hold the key to flood prevention through desynchronization of flow is also involved.

To manage the snowpack to prevent floods produced by rain on snow and spring snowmelt, we need to develop procedures that permit accurate prediction of snowpack contributions to floods based on the size of the pack, the meteorological factors, and the interactions between them and aspect, slope, elevation, and vegetation patterns. Second, means of hastening or slowing snowmelt should be studied further. These would involve reforestation, various kinds of cutting on strategic areas, and sowing from the air of chemical substances that alter snowmelt.

Erosion—Sedimentation —Water Quality

Tomorrow's control techniques will probably include greater attention to erosion control and greater use of the forest to improve water quality. Use of the dilution potential obtained by increased water yield, possibly with the aid of detention structures or controlled snowmelt, should be studied further. The effect of forest cover and its management on the biology and chemistry of water bodies must be better understood.

Erosion control is easier when surface disturbance has been held to the minimum by use of overhead logging systems—whether balloon, helicopter, or skyline systems. Faster logging by more use of improved equipment can also reduce the exposure time for disturbed areas and permit earlier installation of control measures.

The future use of forestry to increase water yield and control floods and erosion will depend on the imaginative wedding of insights offered by research to the ever-growing battery of techniques and equipment for inventory and computations. These may be illustrated by some speculations bearing on management of snow basins (Anderson 1966):

> Inventory techniques around the corner include machine interpretation of aerial photos, including such simple inventory characteristics as forest species, densities, and tree heights, but also including special characteristics such as radiation, extent of snow cover, and snow volumes (as in cornices). Instruments for aerial appraisal of the depth and densities of the soil and fractured rock mantle in mountain watersheds hold promise of becoming available . . .
>
> Snow physics research will give a basis for prediction of snow and snow water behavior. The alternative is "cut and try tests" on the some 6,000 different "forest sites" of the West. Further understanding of heat and water budgets, together with knowledge of surface winds and turbulence, may serve to explain the extreme variation in snow accumulation, snowmelt, and evapotranspiration loss. Such explanations will inevitably lead to better designed management techniques and reduction in the number of experimental tests that need to be made of alternative techniques.
>
> Some testing of management techniques by controlled experiments may quite possibly be accomplished largely by finding and evaluating analogous situations in nature. Interactions of forests and terrain seem to be suited to such testing by selection. Other

experimental testing obviously involves laboratory and field tests. Methods of control of the melting of snow, such as by albedo control, need further development. Control of evaporation and condensation of snow by chemicals, such as the long-chain alcohols, should be pursued. Further tests of control of snow drifting, of piling snow by avalanche initiation, and of creation of artificial glaciers might be considered. The soil-water "reservoir" is practically uninvestigated from the viewpoint of management of its characteristics, except by simple resorting to vegetation removal and type conversion. Sterilization of the deeper soil layer to prevent root penetration and transpiration losses seems possible.

The prospects for management of forests for water are bright. Goodell (1965) has set for the proper goal:

> The culture of the forest so that there is no water wasted by plant material that is neither economically important, necessary to the protection of the soil or of water quality, nor necessary to the production of wood of desired specifications.

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