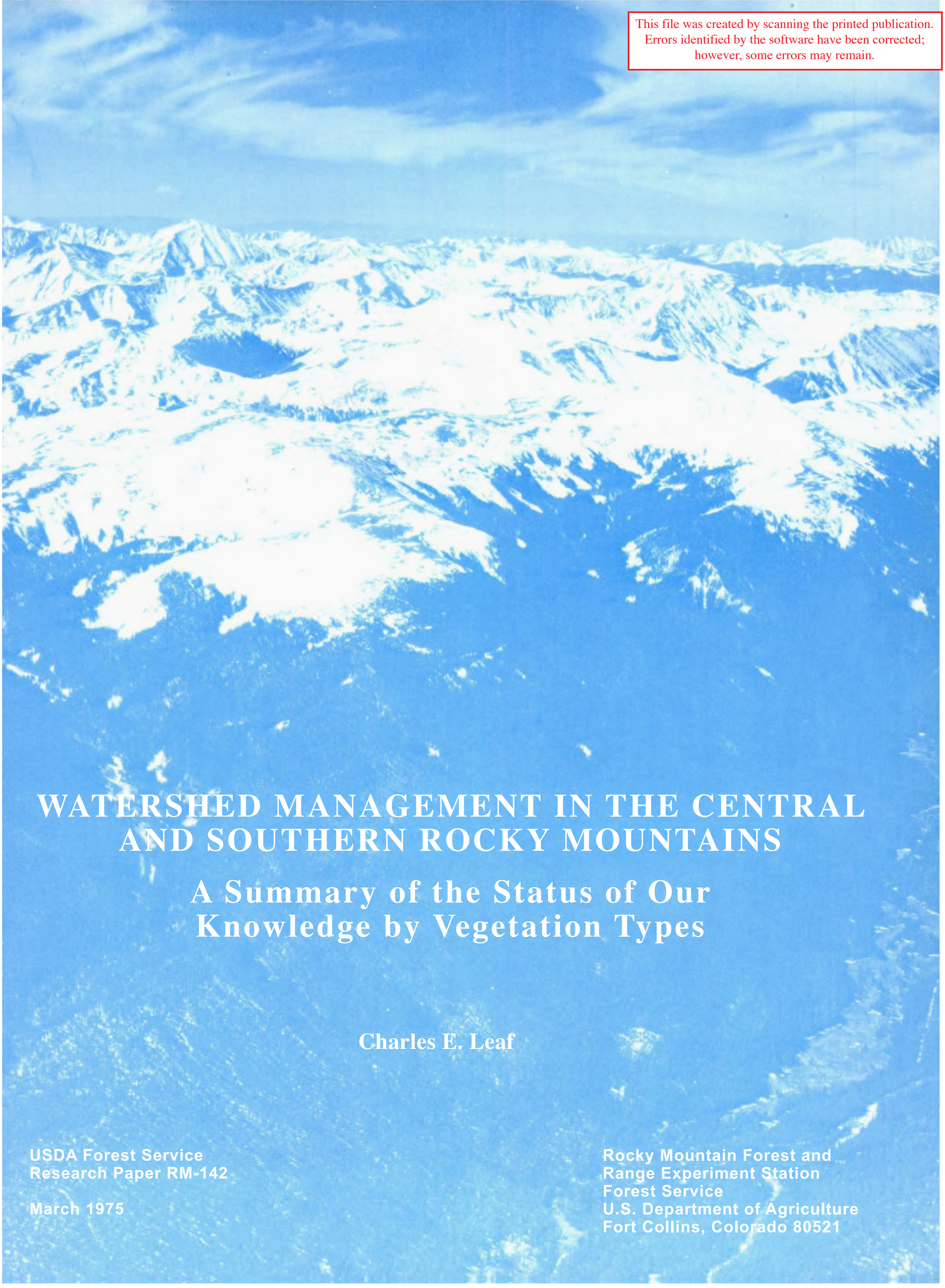

WATERSHED MANAGEMENT IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS

A Summary of the Status of Our Knowledge by Vegetation Types

Charles E. Leaf

USDA Forest Service
Research Paper RM-142

March 1975

Rocky Mountain Forest and
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Fort Collins, Colorado 80521

Abstract

Summarizes a series of comprehensive reports on watershed management in five major vegetation zones: (1) the coniferous forest subalpine zone; (2) the Front Range ponderosa pine zone; (3) the Black Hills ponderosa pine zone; (4) the alpine zone; and (5) the big sagebrush zone. Includes what is known about the hydrology of these lands, what hydrologic principles are important for multiresource management, and what additional information is needed for each vegetation type.

Keywords: Watershed management, land use planning, alpine hydrology, range hydrology, snow hydrology, blowing snow management, water yield management.

PREFACE

Comprehensive reports on the status of our knowledge in watershed management, applicable to the important central and southern Rocky Mountain vegetation types, have been prepared as Research Papers by the Rocky Mountain Forest and Range Experiment Station. These include:

> “Watershed management in the Rocky Mountain Subalpine Zone: The Status of Our Knowledge,” by Charles F. Leaf, (RM-137),
> “Water-Yield Improvement From Alpine Areas: The Status of Our Knowledge,” by M. Martinelli, Jr., (RM-138),
> “Watershed Management Problems and Opportunities For the Colorado Front Range Ponderosa Pine Zone: The Status of Our Knowledge,” by Howard L. Gary, (RM-139),
> “The Hydrology of Big Sagebrush Lands: The Status of Our Knowledge,” by David L. Sturges, (RM-140), and
> “Watershed Management in the Black Hills: The Status of Our Knowledge,” by Howard K. Orr (RM-141).

These papers have been condensed in the report to provide a general summary of what is currently known about watershed management in all the major vegetation zones of the central and southern Rocky Mountains. Acknowledgments and literature citations are included in the full-length papers.

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WATERSHED MANAGEMENT IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS:

A Summary of the Status of Our Knowledge by Vegetation Types

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WATERSHED MANAGEMENT IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS:

A Summary of the Status of Our Knowledge by Vegetation Types

Charles F. Leaf

INTRODUCTION

Watershed management in the central and southern Rocky Mountains includes land use practices varying from manipulation of forest and range vegetation to building fences upwind of natural snow accumulation areas. The effectiveness or desirability of these practices depends on how well management goals consider the inherent hydrologic characteristics of a given area, vegetation type and condition, and environment. All these factors affect the quantity, quality, and timing of runoff. Because most undisturbed hydrologic systems are in dynamic equilibrium, the resource manager must be certain that natural processes are not altered by land use to the extent that undesirable hydrologic changes result.

Although not all limiting factors and optimum watershed management practices have been identified in the Rocky Mountain region, research has produced more information than is presently being used in day-to-day decision-making. Although a few summary publications and textbooks are available on the subject, most research results and observations during the last 40 years have been presented as individual articles, papers, and notes in a variety of publications. Moreover, much of what is presently known has not been documented in the literature. Accordingly, it is in the best interest of the profession to periodically synthesize and organize published as well as unpublished research results into one source.

The comprehensive status-of-knowledge summaries prepared for each vegetation type are intended to guide professional hydrologists and resource managers by providing information on: (1) what is known about the hydrology of the principal vegetation zones, and (2) how this knowledge can best be applied to meet multiresource management objectives. Supplemental benefits resulting from this effort include detailed literature reviews and identification of knowledge gaps where additional research is needed.

The purpose of this document is to provide a broad overview and evaluation of the more detailed status-of-knowledge reports. It is subdivided into five main sections: The Coniferous Forest Subalpine Zone, The Front Range Ponderosa Pine Zone, the Black Hills Ponderosa Pine Zone, the Alpine Zone, and finally, the Big Sagebrush Zone. Literature reviewed is not cited in this summary Paper, but is included in each of the five reports listed in the Preface.

THE CONIFEROUS FOREST SUBALPINE ZONE

Lodgepole pine and Engelmann spruce-subalpine fir forests characterize the subalpine zone (fig. 1). Lodgepole pine is the principal tree species in Wyoming, and occupies mountain slopes between 7,000 and 10,000 feet. Subalpine forests in Colorado range from 8,500 to 11,500 feet above sea level, and straddle the entire length of the Continental Divide from north to south across the State. Forest cover between 8,500 and 10,500 feet is lodgepole pine, quaking aspen, and Douglas-fir. Spruce-fir forests grow between 10,000 and 11,500 feet. In New Mexico, Douglas-fir and spruce-fir are the principal forest types. The former grows between 8,000 and 9,500 feet, whereas the latter is found above this elevation.

WHAT WE KNOW ABOUT SUBALPINE HYDROLOGY

Climate, Geology, and Water Yield

The climate of the subalpine zone is cool and humid. The mean annual temperature is less than 35°F, and precipitation, which falls largely as snow, averages about 28 inches.

Soils are derived from crystalline granites, and gneiss and schist rocks. Sedimentary and volcanic parent material are also common. Most valleys contain alluvial soils. Boggy areas, which owe their origin to seeps and springs, contain highly organic soils. For the most part, subalpine soils are relatively deep, permeable,

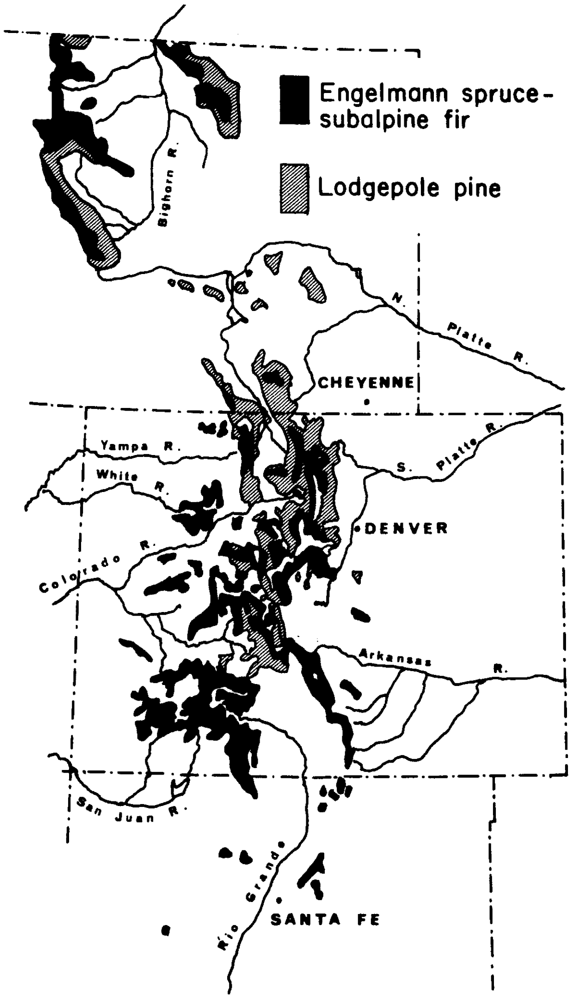


Figure 1.—Distribution of spruce-fir and lodgepole pine forests that comprise the subalpine zone in Wyoming, Colorado, and New Mexico.

and capable of storing modest quantities of water from snowmelt. Exceptions occur in those areas which have experienced intensive glacial activity. Here, soils are shallow, and runoff is concentrated during a short snowmelt period.

Snowmelt produces virtually all of the streamflow required by agriculture, industry, and municipalities. Spring runoff begins in late March or early April, peaks in early June, and recedes to base flow levels by mid-October. Streamflow averages between 12 and 15 inches annually. Mean annual water balances for typical subalpine watersheds in Colorado and Wyoming are summarized in table 1.

Table 1.--Mean annual water balances (inches) for typical subalpine watersheds in Colorado and Wyoming

Watershed	Seasonal snowpack, water equivalent	Precipitation	Evapotranspiration	Runoff
COLORADO:				
Soda Creek, Routt NF	42.6	55.2	16.7	38.5
Fraser River, Arapaho NF	15.0	30.3	16.9	13.4
Wolf Creek, San Juan NF	26.2	48.0	21.0	27.0
Trinchera Creek, Sangre de Cristo Mountains	9.5	19.6	14.5	5.1
WYOMING:				
South Tongue River, Bighorn NF	15.5	29.6	15.8	13.8

Snow Accumulation

Snow input can be precisely measured on accessible forested watersheds. Areal snow storage can be estimated from reconnaissance snow courses where one or two samples at most are taken at intervals along a trail which traverses the whole watershed. On uniformly forested watersheds, where melt rarely occurs during winter, snow storage can be estimated to within 5 percent of the true mean with 50 samples per square mile widely spaced over the drainage basin.

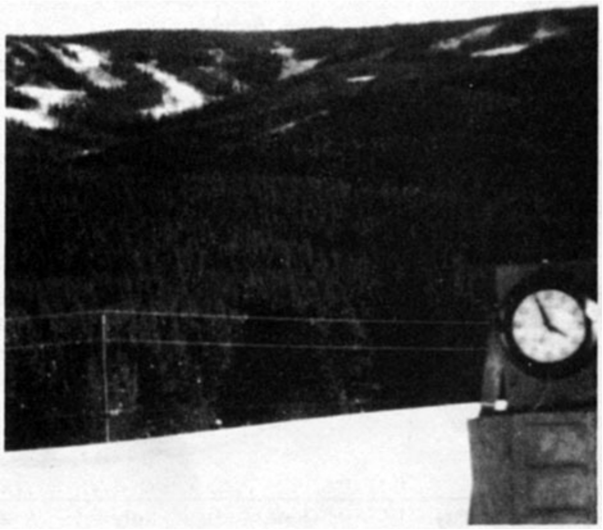
Where severe winds produce extremely irregular patterns of snow accumulation in forest margins and exposed parklike openings, reconnaissance snow courses can precisely estimate areal snow storage, provided that sampling intensities in and near the edge of large openings are 8 to 10 times greater than well inside the surrounding forest.

Partial cutting on areas less than 10 acres in old-growth lodgepole pine increases the snowpack in amounts proportional to the timber removed. Increases are optimum in clearcut patches five to eight times tree height and protected from wind. More snow is deposited in the openings and less under the adjacent uncut forest, so that total snow storage on an area basis is unchanged. Increased snow accumulation in the openings can be expected to persist for at least 30 years and longer, despite vigorous regrowth, due to the aerodynamic effect on snow distribution. After a typical snowfall event, wind-generated vortexes and eddies quickly strip intercepted snow from trees. In a short time, this airborne snow is redeposited at varying distances from where it was initially intercepted. Ultimately, virtually all the snow is removed from exposed tree crowns. The sequence of events in figure 2 illustrates the obvious importance of wind-caused snow redistribution in the subalpine zone.

Figure 2.—Significance of wind-caused snow redistribution in subalpine forest:

This photograph was taken during moderate snowfall that continued throughout the day on February 4, 1970 at the Fraser Experimental Forest. The storm ceased during the night.

The most exposed trees were already bare of snow by noon on February 5, 1970. Individual vortexes look like artillery bursts on the mountainsides. Vortexes were moving rapidly eastward (from right to left), and each one was visible for less than 60 seconds.



By 4:00 p.m. on February 5, 1970, all snow was gone from exposed tree crowns. The white patches are snow in the clearcut blocks on the upper portion of the Fool Creek watershed.

Evapotranspiration

Model studies of an unripened snowpack indicate that substantial amounts of water vapor are lost from the deepest layers of the pack. Free convection can take place within the pack during winter, and evaporation from surfaces can be relatively high during clear weather in late spring.

Both spruce and aspen can remove soil moisture to 8 feet in deep soils. The rate of water use by forest vegetation is related to availability. On low-elevation south slopes, soil-moisture deficits are sufficient to limit transpiration during dry years. Transpiration can occur early in the melt season when there is still considerable snow cover. Soil moisture is withdrawn largely from the upper part of the soil mantle during early spring. Later in the season, however, soil moisture in the deeper layers is required for transpiration demands.

Level-of-growing-stock studies have shown that only when a timber stand is thinned to approximately one-fifth of its original density, is soil-moisture withdrawal sharply reduced. Fall soil-moisture deficits in the top 6 feet of small patchcut openings are substantially less than in the surrounding uncut forest. Accordingly, less water is needed in spring to recharge soil moisture in cutover areas, and there is more available for streamflow.

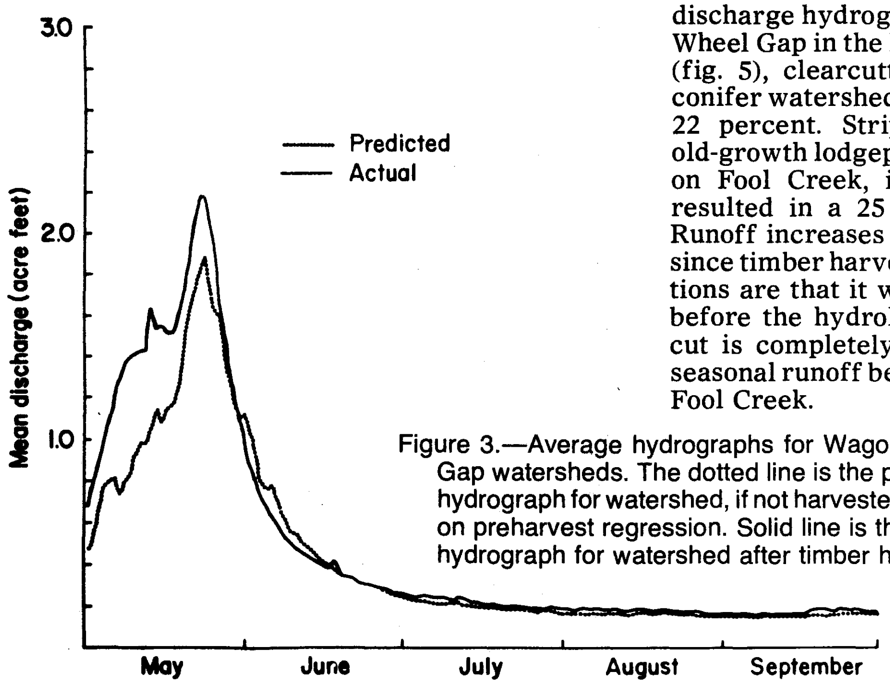


Figure 3.—Average hydrographs for Wagon Wheel Gap watersheds. The dotted line is the predicted hydrograph for watershed, if not harvested, based on preharvest regression. Solid line is the actual hydrograph for watershed after timber harvest.

Snowmelt and Runoff

Snowmelt rates on forested watersheds with generally east- and west-facing aspects are generally uniform at all elevations. In contrast, snowmelt rates on watersheds with north- and south-facing slopes differ considerably at low elevations. However, the time lag between maximum snowmelt rates on north and south slopes diminishes with increasing elevations.

Water-yield efficiencies are highest on watersheds that have (1) almost complete snow cover when seasonal snowmelt rates on all major aspects are uniform, (2) a delayed and short snow-cover depletion season, and (3) moderate recharge and evapotranspiration losses.

Water-yield efficiencies are least on low-elevation south slopes. Below 9,800 feet, streamflow can be less than 30 percent of that generated at higher elevations. Water yields from low-elevation north-south subdrainages can vary from near zero in poor runoff years to a maximum during good years of less than 60 percent of the flow generated from high-elevation subdrainages with north and south aspects.

Snowmelt rates are more rapid in patchcut areas than in uncut forest. Moreover, faster melt rates are offset by higher snow accumulation in small patchcuts so that open and forested areas become bare of snow simultaneously.

Accelerated snowmelt resulting from timber harvesting is conspicuous in the discharge hydrograph (figs. 3 and 4). At Wagon Wheel Gap in the headwaters of the Rio Grande (fig. 5), clearcutting a 200-acre aspen-mixed conifer watershed increased water yields about 22 percent. Stripcutting 40 percent of the old-growth lodgepole pine and spruce-fir forest on Fool Creek, in central Colorado (fig. 6), resulted in a 25 percent increase in runoff. Runoff increases may have begun to taper off since timber harvest in 1955, but current indications are that it will be at least 30 more years before the hydrologic impact from the initial cut is completely erased. Figure 7 compares seasonal runoff before and after stripcutting on Fool Creek.

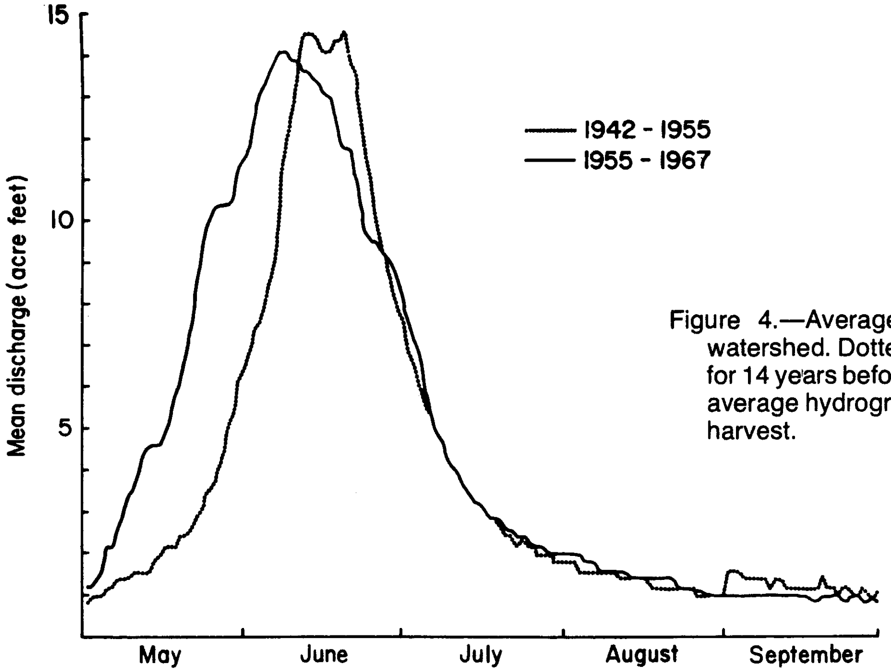
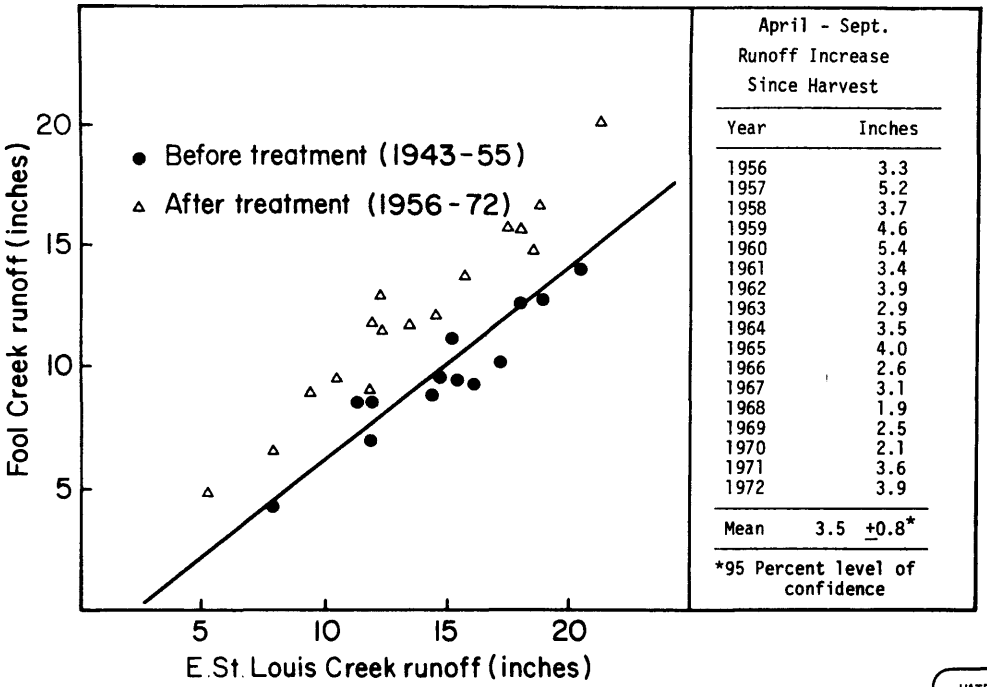


Figure 4.—Average hydrographs for Fool Creek watershed. Dotted line is the average hydrograph for 14 years before timber harvest. Solid line is the average hydrograph for 13 years following timber harvest.

Figure 5.—The Wagon Wheel Gap watersheds some 30 years after treatment. The regenerated forest cover on the clearcut watershed at right is aspen. The control watershed on the left is still vegetated with aspen and mixed conifers.

Figure 6.—
Fool Creek watershed, Fraser Experimental Forest. Control watershed is to the right of Fool Creek.



April - Sept.
Runoff Increase
Since Harvest

Year	Inches
1956	3.3
1957	5.2
1958	3.7
1959	4.6
1960	5.4
1961	3.4
1962	3.9
1963	2.9
1964	3.5
1965	4.0
1966	2.6
1967	3.1
1968	1.9
1969	2.5
1970	2.1
1971	3.6
1972	3.9
Mean	3.5 ±0.8*

*95 Percent level of confidence

Figure 7.—Comparison of seasonal runoff before and after strip cutting on Fool Creek watershed.

Runoff probably is not significantly changed under accepted intensities of cattle grazing on watersheds with extensive grassland parks. Reasons for this are: (1) virtually all of the streamflow and sediment yield is produced during the snowmelt runoff season, (2) 60-minute rainfall intensities seldom exceed 1 inch per hour, and (3) grazing intensities are normally set up to obtain 25 to 60 percent utilization of range species, such as Idaho fescue.

Hydrologic Systems Analysis

Dynamic simulation models specifically designed to determine the short- and long-term hydrologic changes resulting from timber harvesting in the subalpine zone are now available for use by resource managers. Corollary models simulate timber yields. Emphasis is placed on the "planning unit," which is defined by environmental characteristics including slope, aspect, elevation, and forest cover. The hydrologic model (Subalpine Water Balance Model) simulates winter snow accumulation, the shortwave and longwave radiation balance, snowpack condition, snowmelt, and subsequent runoff in time and space.

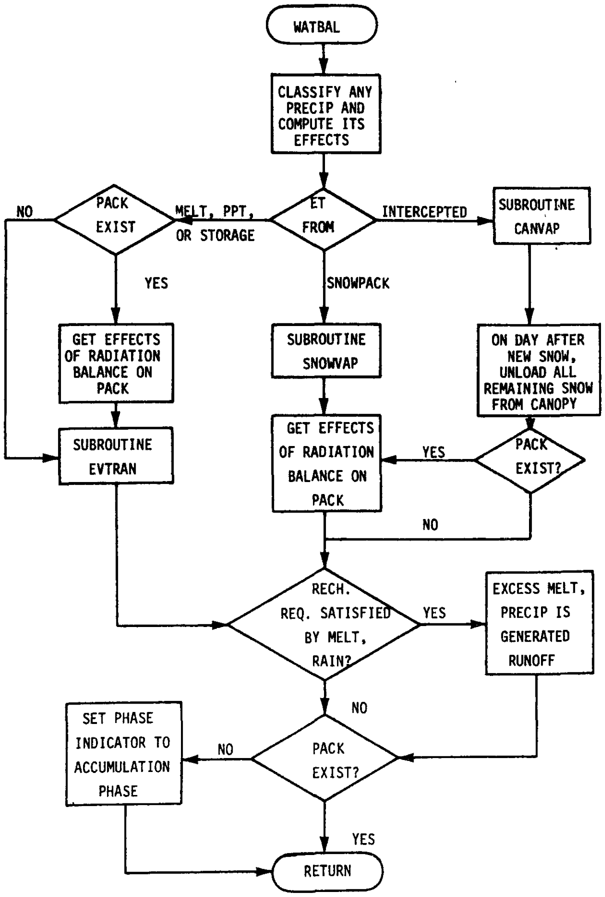


Figure 8.—Flow chart of dynamic model that simulates subalpine hydrology.

The model is capable of simulating the hydrologic impacts of a broad array of watershed management alternatives which can include weather modification, forest cover manipulation, or combinations of both practices. Figure 8 is a flow chart of the system. When timber is harvested, hydrologic change can be determined for intervals of time which can vary from a few years to the rotation age of subalpine forests. This is accomplished by means of time-trend functions in an expanded version (Subalpine Land Use Model) which computes changes in evapotranspiration, soil water, forest cover density, reflectivity, interception, and snow redistribution as the forest stands respond to management (fig. 9).

The models have been used to simulate the hydrologic impacts of forest and watershed management on five representative drainage basins in the Rocky Mountains. Detailed simulation analyses of hypothetical watershed management practices including weather modification and timber harvesting are presented in the conprehensive status-of-knowledge summary for the subalpine zone (RM-137).

The system developed for the subalpine coniferous forest zone represents our first step in providing the resource manager with planning tools which utilize our best technical understanding of fundamental hydrologic processes. The models have been designed so that they are no more complex than required to provide necessary information for planning. Moreover, use of the models is not unduly restricted by data requirements. Basic hydrologic data currently available are adequate for operational use in most areas.

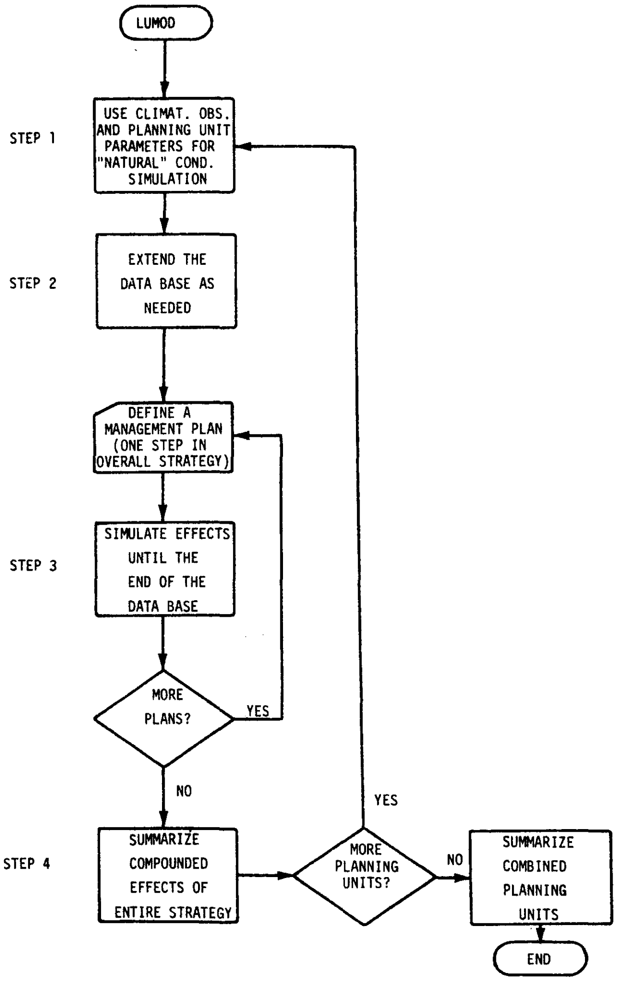


Figure 9.—Flow chart showing how the hydrologic simulation model is used to execute long-term alternative management strategies.

Erosion and Water Quality

Sediment Yield

Bedload and suspended sediment need not be excessive in central Colorado, provided reasonable erosion control measures are applied during logging and road construction. Sediment yields are increased in the years during and immediately after initial disturbance, but decrease rapidly in subsequent years toward preharvest levels.

Prediction equations which require erodibility indices based on rainfall intensity may be grossly in error when applied to much of the subalpine zone, where the runoff that transports much of the sediment load results from melting snow. Moreover, when rainfall-index equations are used, it is difficult to account for the obvious reduction of sediment yield with time. Accordingly, a simple model based on observed data has been developed to predict the impacts of secondary logging road construction.

The time-trend equation is used in combination with another expression which computes the area disturbed by road construction. This equation is formulated in terms of the following watershed and engineering design parameters: (1) width of roadbed, (2) average watershed sideslope, (3) number of miles of road system, and (4) angle of cut and fill. Because the model is formulated in terms of engineering design variables, its use should provide an estimate of the erosion impacts of alternative road systems. The model is based on field data collected from a stable subalpine watershed, and a carefully constructed secondary road system with a high standard of followup maintenance. Any direct application of the model should presume similar conditions.

Chemical and Bacterial Water Quality

In general, concentrations of all chemical water-quality components in subalpine streams are low. The pH values are near neutral, and water temperatures are cold (0° to 7°C). The chemical composition, in parts per million, of representative subalpine streams is summarized below:

Component	**Concentration** *(p/m)*
Ca	1.8 - 14.5
Mg	0.8 - 6.5
Na	1.0 - 4.5
K	0.4 - 1.0
CO_2	1.6
HCO_3	18.9
Cl	3.0 - 5.0
SO_4	10.0 - 14.6
NO_3	0.8 - 1.0
SiO_2	0.8

Bacterial counts can vary from several million colonies per milliliter down to less than 10,000 colonies per 100 milliliters. Generally, a strong positive bacteria-to-flow relationship can be expected. High bacterial concentrations associated with grazing and recreation impact appear to depend on the "flushing effect" during peak snowmelt and summer storm runoff periods. A seasonal trend for coliform, fecal coliform, and fecal streptococcus can be expected according to the following sequence: (1) low winter counts prevail while the water is near 0°C, (2) high concentrations appear during times of peak snowmelt, (3) a "post-flush" lull takes place as hydrograph declines in midsummer, (4) high concentrations are found again in the late summer period of warm temperatures and low flow, and (5) concentrations are sharply reduced in fall. All three bacteria can be expected in subalpine streams.

HYDROLOGIC PRINCIPLES IMPORTANT TO MULTIRESOURCE MANAGEMENT OF THE SUBALPINE ZONE

The task of recommending specific forest management practices is left to the resource manager after he has considered all feasible alternatives. The following paragraphs highlight technical aspects of the status of knowledge in watershed management, and summarize principles which should be considered in multiresource management of the subalpine zone.

- Patchcutting subalpine forests results in significant redistribution of the winter snowpack. An optimum pattern of snow accumulation results when openings are: (1) less than eight tree heights in diameter, (2) protected from wind, and (3) interspersed so that they are five to eight tree heights apart. More snow is deposited in the openings, but less snow accumulates in the uncut forest, so that total snow on headwater basins is not significantly increased.

- Snowmelt in patchcut openings on all aspects is more rapid than in the uncut forest. This accelerated melt causes streamflow to be higher on the rising limb of the hydrograph than during preharvest conditions. Where there is considerable natural regulation in the form of deep porous soils, recession flows apparently are not changed appreciably, and annual flood peaks are not significantly increased **provided that** the forest cover on no more than 50 percent of the watershed is removed in a system of small openings.

- When 40 percent of a densely forested subalpine watershed is occupied by small openings, and 60 percent is left uncut, annual water yields may increase as much as 2 to 3 inches above the norm. Interception loss is decreased, but increased evaporation from snow surfaces in the openings almost compensates for the decreased interception. Average fall soil-water recharge requirements are decreased, as is evapotranspiration during the growing season. Simulation analyses indicate that, under this alternative, water-yield increases on low-elevation south aspects in lodgepole pine forest are as large as corresponding increases from high-elevation north aspects in spruce-fir. Hence there is no reason to favor areas with the highest natural water yield if the objective is to maximize water yields from medium to dense old-growth forest.

- The **pattern** in which trees are harvested determines whether or not runoff will be increased. Highest increases in streamflow result when subalpine forests are harvested in a system of small forest openings. When the forest cover is removed in large clearcut blocks, or by selectively cutting individual trees, overall water increases are far less than that attained if an equivalent volume is removed in patches. When 40 to 50 percent of the mature spruce-fir timber volume is removed from north slopes on a selection-cut basis, water yields may actually decrease somewhat. In lodgepole pine forest, water yields can be increased somewhat by this method, provided that selection cuts are made on southerly aspects and at low elevations where the snowmelt season is short and begins relatively early in the spring.

- The harvesting measures recommended for maximum water yields are silviculturally sound and compatible with timber management guidelines recently developed and published in a comprehensive status-of-knowledge paper (RM-121). This paper, also published by the Rocky Mountain Station, carefully considers the ecology, silviculture, and management of subalpine forests; it recommends practices for water-yield improvement which would also enhance wildlife habitat, and preserve the natural landscape in areas where recreation and esthetics are important.

- It is not expected that the timber-harvest measures recommended for maximum water yields from the subalpine zone will be detrimental to water quality or excessively increase erosion, **provided that** timber is harvested with proper planning, engineering, construction, and followup maintenance. Although sediment yields can be expected to increase immediately following road construction, yields decrease rapidly toward preharvest levels after a short time. It is important to understand that these conclusions apply only to **surface erosion,** not **mass erosion,** which can occur if very steep and naturally unstable slopes are disturbed.

- Results from simulation analyses have indicated that, in central Colorado, a 15 percent increase in snow accumulation through successful weather modification will increase water yields 16 percent in the average year. In general, the increased snowpack will not extend the snowmelt season more than 3 to 5 days. Because water-yield benefits result from the last snowmelt at a given location, the bulk of the increased runoff is released during and just after peak streamflow. This would have a tendency to broaden the snowmelt hydrograph by increasing recession flows, and increase peak flows to some extent in small headwater streams. If increased snowfall due to weather modification is combined with patchcutting, water-yield increases will be even greater. In central Colorado, for example, where 40 percent of a given watershed is occupied by forest openings five to eight tree heights in diameter, water-yield increases can be doubled if the natural snowfall is increased by 15 percent.

- Dynamic simulation models have been developed from the best information we presently have about subalpine hydrologic systems. The models have been calibrated, using data from representative watersheds in old-growth lodgepole pine and spruce-fir forests throughout the Rocky Mountain region. They have been designed to predict the short- and long-term hydrologic impacts of a broad array of watershed management practices. Hydrologic changes can be determined for intervals of time which can vary from a few years to the rotation age of subalpine forest. The models produce expected results based on experience and our status of knowledge. We believe that the output from such models contains the type of information professional hydrologists and land managers need to know in order to make difficult management decisions. The ability of these and other similar models to integrate complex forest and water systems make them unique and powerful tools for evaluating the hydrologic and environmental impacts of a broad array of land management alternatives.

WHAT DO WE NEED TO KNOW

Techniques of precipitation measurement, including snow surveys and ground-based sensors, need to be improved. Although this problem has been researched for several hundred years, much of what has been done has largely reaffirmed past results without producing new knowledge. New and different systems, such as laser devices or particle counters, offer promise of better precipitation measurement in the future.

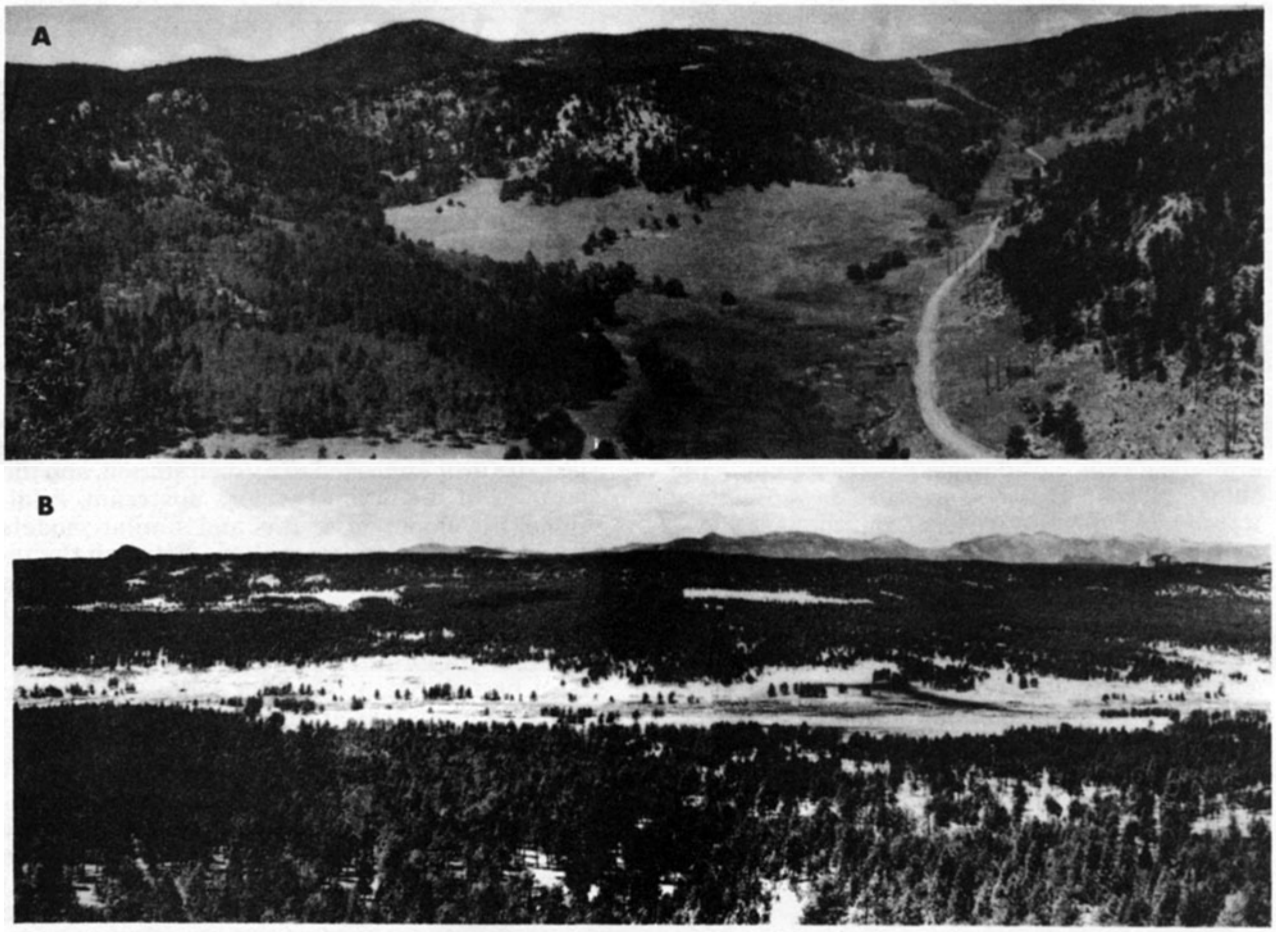
A novel simulation model recently proposed suggests that total snowfall in mountainous areas can be explained by the topographic slope which airmasses must traverse on the last 20 km of approach to a given station, and the number of mountain barriers upstream. Additional development of this and similar models which account for interactions between the topography and large airmasses will result in highly useful tools for explaining the seasonal snowfall distribution on a regional basis. Another important benefit from their use will be a better insight into the complex dynamic physical processes affecting mountain precipitation regimes.

A better knowledge of aerodynamic processes that affect interception and differential snow accumulation is yet to be gained. New work in (1) characterizing the aerodynamic characteristics of subalpine timber stands, (2) evaluation of the long-term effects of tree height growth on snow accumulation, and (3) sublimation losses from transported snow, will significantly add to what we have already learned from empirical studies.

At the present time, we do not have a complete understanding of evapotranspiration on an areal basis. While empirical methods have been useful for quantifying consumptive use, our knowledge of basic forest-water relationships is far from adequate.

The complex problem of quantifying the interaction of solar radiation with subalpine forest canopies needs more attention. This work should concentrate on the interrelated factors involved in the time-dependent variability of the radiation balance above and beneath forest canopies. It should consider solar geometry, the orientation of intercepting slopes, and the absorptive, transmissive, and scattering properties of canopies. Of highest priority are studies which objectively define the radiation balance in terms of such forest vegetation parameters as basal area, crown depth, stem density, and other indices of foliage mass and distribution.

One of the most controversial impacts of land use is road construction. Yet, little information is currently available on the natural levels of sediment yield from subalpine streams. Although some bedload data have been collected from experimental watersheds, more of this type of information is needed on representative watersheds throughout the Rocky Mountain region. There is much yet to be learned about other aspects of water quality, including suspended sediment, water chemistry, and bacterial water quality. These parameters are of interest in a wide range of problems which can vary from nutrient balance changes associated with timber harvesting to the disposition and survival of pathogenic bacteria resulting from winter recreation activities in wilderness areas.



THE FRONT RANGE PONDEROSA PINE ZONE

The Colorado Front Range, generally thought of as the eastern foothills region of the Rocky Mountains, extends from southern Wyoming to the vicinity of Canon City, Colorado. On the east, it is bounded by high plains; on the west it reaches the Continental Divide. The low-elevation (6,000 - 9,000 feet m.s.l.) forests and grasslands are generally and collectively called the ponderosa pine, or Montane Zone (fig. 10).

Commercially valuable tree species above 7,000 feet elevation are ponderosa pine, lodgepole pine, Douglas-fir, and Engelmann spruce. Much of the forest cover has been cutover, beginning with early settlement of the Front Range. Aspen is also an inportant tree species in young stands, particularly where fire has occurred. Brush species grow at the lower elevations on south exposures and on old burns. The interspersed grasslands are important forage producers for cattle (fig. 11). Many of the valleys were farmed near the turn of the century, but have since been abandoned because of low rainfall, erosion problems, and short grow-

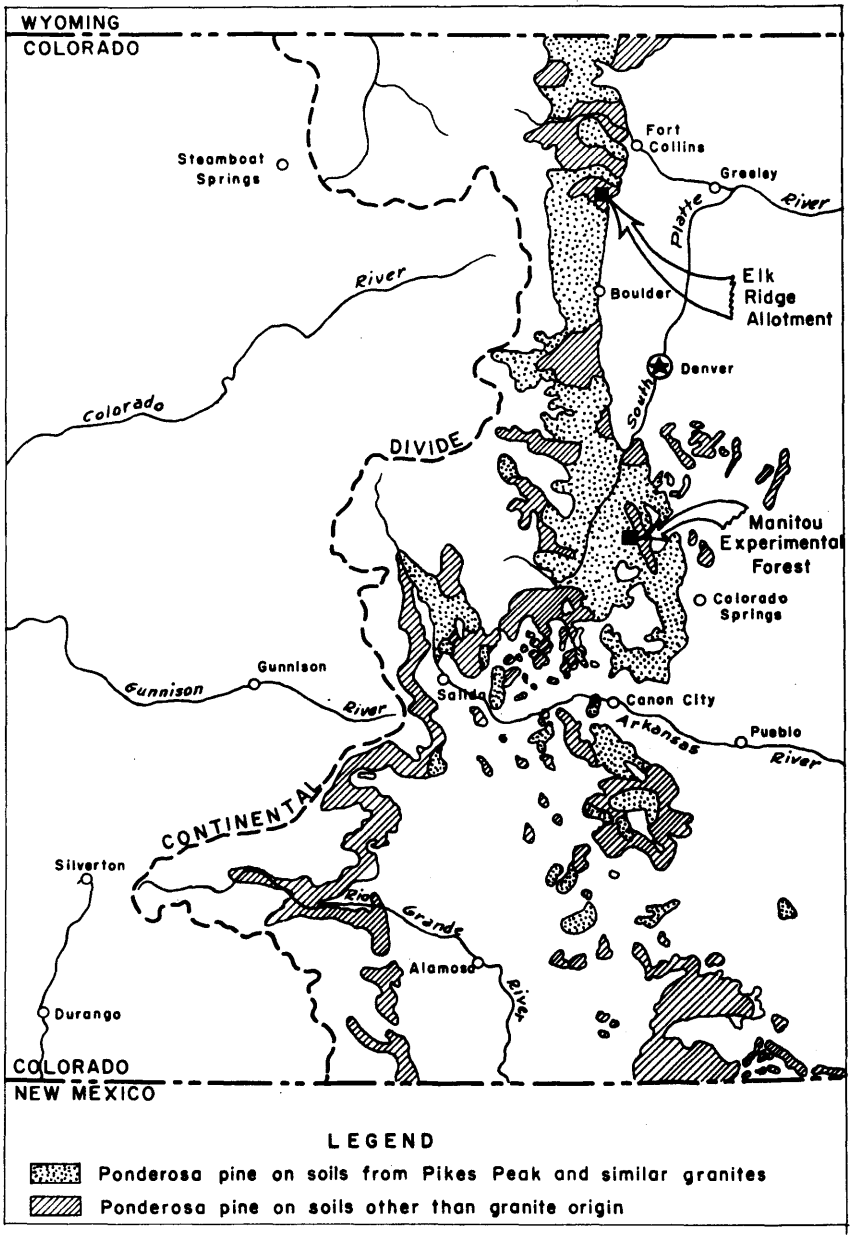


Figure 10.—Distribution of the ponderosa pine type along the Colorado Front Range in relation to soil origin.

Figure 11.—Panoramas typical of the Front Range pine type: **A**, the North Fork of the Little Thompson watershed; **B**, the Manitou Experimental Ranges.

ing season. Today, recreation use and residential development in the Front Range probably have impacts as high as any other single use.

WHAT WE KNOW ABOUT FRONT RANGE HYDROLOGY

Climate, Geology, and Water Yield

The climate of the region is typically subhumid, with wide diurnal and annual temperature ranges and great variation in the amount and distribution of precipitation. Precipitation may be in the form of snow from late September through May, but snow commonly melts from areas exposed to radiation within a few days. The shallow snowpacks at high elevations and on protected north slopes generally disappear by mid-May. Annual precipitation probably averages between 15 and 20 inches. About two-thirds occurs in April to September, and thus accounts for the presence of grass over much of the area.

The Montane Zone is subject to intensive rainfall and infrequent but major floods. Flooding can occur from high-intensity rainfall confined chiefly below 7,000 feet and extending eastward from the foothills for a distance of about 50 miles. Such storms are generally confined to small areas and last for a short time. Perhaps the most devastating flooding can occur in May or June from moderate-intensity upslope storms which produce large quantities of precipitation over a period of 3 to 5 days. Above 7,000 feet, most of the precipitation from spring storms falls as snow.

Rainfall and flooding in the Front Range produce significant geologic as well as hydrologic effects. Geologic processes triggered by such floods can be intensified by improper land use, causing heavy property damage and even loss of life.

Land features along the Front Range are complex, and vary from steep rocky canyons to large openings and parks. Soils, for the most part, have developed from coarse granite rocks, alluvial deposits, sandstones, limestones, and quartzites. The most stable soils are developed from limestone, while the shallow and potentially unstable soils are derived from granite. Limestone and deep alluvium soils support more herbaceous vegetation and forest cover than do the less fertile granitic soils. The latter occur over about 90 percent of the area. Seeps, springs, and wet meadows are common throughout the Front Range, and occupy about 2 percent of the area.

The potential water balance for a typical Montane Zone watershed is shown in figure 12.

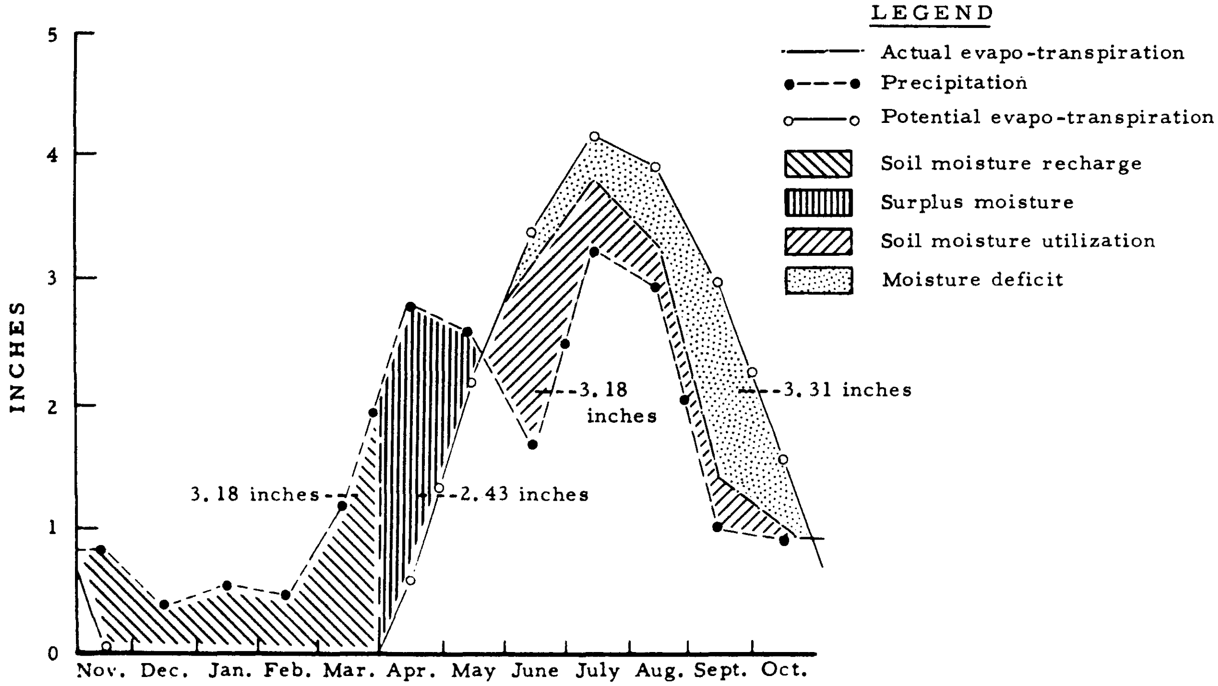


Figure 12.—Potential water balance for Missouri Gulch watershed, Manitou Experimental Forest.

The values indicate that annual precipitation is in excess of potential evapotranspiration from November through May. Thereafter, the balance is characterized by a substantial moisture deficit when evapotranspiration depletes soil-water storage. Accordingly, streams originating in the low-elevation pine type are usually intermittent and flow only during late fall, winter, and spring.

Average annual water yields can vary from approximately 12 inches in lodgepole pine and spruce-fir forests near the Continental Divide to less than 5 inches, or about 15 percent of the annual precipitation, in the Front Range pine zone. Near the upper limits of the ponderosa pine type, runoff is approximately 6 inches during the average year.

Watershed-Condition Criteria

Certain plant species and associations apparently have more effect than others on infiltration, runoff, and erosion. The effectiveness of any species or type is significantly influenced by organic materials and physical soil properties. Litter and porosity of the surface soil are the two factors most highly correlated with rainfall infiltration rates.

Cattle grazing and other land use affects infiltration by destroying plant cover and reducing the proportion of noncapillary pores. On-the-ground organic materials exceeding 2 tons per acre, exposed soil less than 30 percent, and noncapillary pores exceeding 20 percent in the upper 2 inches of soil constitute satisfactory watershed conditions from the standpoint of runoff and erosion from Montane grasslands.

On steep upland forested areas, organic materials exceeding 2 tons per acre or 1,000 to 1,300 pounds of live herbage per acre produce desirable watershed conditions. Quantity of litter is also an important hydrologic factor in the timber-grass types. Favorable watershed conditions result when 19,000 to 21,000 pounds of litter per acre are maintained.

Channel Erosion and Sediment Yield

Meadows and hillsides are typically lined with gullies throughout the Front Range pine zone (fig. 13). Guides for gully control have long been available, but many gully control structures apparently fail due to a lack of engineering and followup maintenance. Only a few summer storms produce gully flows. While some gully activity is caused by short-duration summer cloudbursts, the most severe erosion probably takes place during large-scale moderate-intensity upslope storms. Associated geologic activity such as rockfalls, slumps, and earthflows can also result from these events.

Figure 13.—Erosion channel through a Front Range meadow.

Reservoir sedimentation is also a significant factor. Sediment yields from one 69 square-mile drainage averaged approximately 0.3 acre-feet per square mile annually for an 11-year record period.

Watershed Management

Forest management in ponderosa pine offers possibilities for increasing water yields. Snow accumulation in small patchcuts five to eight times tree height can be expected to increase from 8 to 35 percent with an associated decrease in snowpack in the adjacent uncut forest, so that total snow storage is not changed. As discussed previously, research in the subalpine zone has shown that increased runoff and higher spring freshets can be expected after patchcutting; these changes affect the snow accumulation pattern and snowmelt timing, and reduce evapotranspiration. The same hydrologic principles apply in the Front Range pine zone.

Management of selected riparian and wet sites supporting trees or willows also offers considerable potential for increasing water supplies. Guidelines on this aspect of watershed management can be found in a recently published status-of-knowledge paper (RM-117) by Horton and Campbell.

Minimal responses in water yield can be expected on grazed lands where soils are deep and highly permeable. When deep-rooted plants are replaced by shallow-rooted species, significant savings in soil moisture are often realized. However, such replacement may not be compatible with the most desirable range management practices, since high forage-producing cover on moderately grazed range has a greater rooting depth and greater potential requirements for soil moisture.

HYDROLOGIC PRINCIPLES IMPORTANT TO MULTIRESOURCE MANAGEMENT OF THE COLORADO FRONT RANGE

- Research has shown that good range management practices and revegetation of depleted land with trees, shrubs, and grass will improve watershed conditions. However, such measures cannot offer complete protection against intense runoff, erosion, transport, and redeposition associated with infrequent severe hydrologic events. It must be recognized that, while improved range and forest management practices are essential in order to avoid triggering and compounding destructive geologic effects, no watershed management practice in itself can prevent normal geologic processes which are characteristic of the Front Range. The impacts of these normal processes will not be intensified, however, if the following watershed-condition criteria are adhered to:

(1) For soils derived from granite and schist on slopes up to 40 percent, organic materials should exceed 2 tons per acre, or 1,000 to1,300 pounds of live herbage per acre. If any area on a 40 percent slope is capable of producing only 1,200 pounds of live herbage without being grazed, then it should be protected from grazing to meet satisfactory watershed criteria. Areas of lesser slope generally produce more than adequate herbage, and may be grazed to the extent that herbage is equal to or greater than the guide figure.

(2) Approximately 19,000 to 21,000 pounds of litter per acre should be maintained on the timber-grass types. Tree cutting should be avoided on areas with lesser amounts of litter and on shallow soils. Areas with greater soil depth may be logged or grazed to the extent where the residual ground cover does not fall below the guidelines.

- Rapid urbanization of the Front Range is bound to increase watershed-protection problems. Of primary concern are hazards created by common land development practices such as road construction, drainage, steepness of natural slopes, building site location, and many related disturbances. Qualified professionals who can recommend those practices which avoid triggering geologic processes, thus compounding intensity and damage from severe hydrologic events, should be consulted prior to development.

- Water yields are important in the Front Range pine zone. Although the 3- to 5-inch yields are comparatively small in contrast to yields exceeding 12 inches from subalpine forests, watershed management practices can be expected to provide feasible solutions to many local water-supply problems with increased competition for this limited resource. The same hydrologic principles for water-yield improvement previously summarized for the subalpine zone are applicable to the Front Range. In forested areas, some form of patchcutting will produce highest runoff increases, whereas selective cuttings will result in small or negligible increases in streamflow.

WHAT DO WE NEED TO KNOW

Knowledge gaps discussed in the previous subalpine zone summary also apply to the Front Range. In addition, more research is needed on the best methods of plant establishment and kinds of plants most adaptable to the rehabilitation of naturally or artificially disturbed areas. The possibility that more livestock will be grazed in the Front Range pine zone raises new questions on improved grazing management and increased herbage production. Other land use practices in this zone, such as road construction, recreation, and urban development, will require additional study in order to formulate desirable multiple use management objectives.

The Black Hills is an isolated forest area covering 5,150 square miles in southwestern South Dakota and northeast Wyoming. Ponderosa pine is the principal tree species. During the past 100 years, much of the area's commercial forests have been cutover at least once. Accordingly, most of the original old-growth stands have essentially been converted to a manageable second-growth forest.

The Hills, while dominated by ponderosa pine, also support almost pure stands of white spruce in stream bottoms and on north-facing slopes. Interspersed with these two conifer species are patches of quaking aspen and paper birch on the more moist sites. Willow, red-osier dogwood, and water birch are also found along many stream bottoms.

Open areas in the form of meadows, parks, and grassland are also common in the Black Hills. Kentucky bluegrass is a dominant grass species, and provides forage for livestock.

WHAT WE KNOW ABOUT THE HYDROLOGY OF THE BLACK HILLS

Climate, Geology, and Water Yield

The climate of the Black Hills is of the Continental type, with wide temperature ranges and nonuniform precipitation. Average annual temperatures are less than 50°F; annual precipitation varies from an extreme 30 inches in the high Hills to 14 to 16 inches toward the Plains. Greatest amounts fall as rain in the spring and early summer. Snow is generally a relatively minor component of annual precipitation, although heavy, wet snows are not uncommon in early to late spring.

During dry years there is little excess water for streamflow, while in average to maximum years, water is available for streamflow and increases with precipitation. Surface yields from the Sturgis watersheds are slightly greater than 7 inches per year, or 25 percent of the annual precipitation. The Black Hills are also vulnerable to extreme flood events. The storm in June 1972 caused unprecedented damage and loss of life.

The area is an erosion remnant consisting of granites which were pushed up beneath overlying sedimentary formations. The exposed granites, sedimentaries, and metasediments are the primary geologic features (fig. 14). The drainage network has a radial-dendritic pattern (fig. 15). Many streams originate on impervious crystalline rock formations and cut through the peripheral sedimentaries. These formations take in, store, and transmit large volumes of runoff, making them an important source of ground water. Much of the time, streamflow is diminished or completely disappears where streams cross sedimentary formations.

In areas of granitic and metamorphic parent material, soils are shallow, coarse textured, and porous. Valley soils are finer textured, deep, and more fertile. Clays and clay-loams are common, particularly where limestone is the parent material.

Water Quality

Concern for water in the Black Hills is focused primarily on quality. While the surface waters are of excellent quality, there are some problems related to the geochemistry of source areas and land and water use. Dissolved solids are low, but surface waters from limestone and related formations contain the largest amounts of essential nutrients.

One of the best-known water-quality problems involves "bog iron," present in some areas of metasediments. Some bog iron has been mined, leaving practically sterile conditions despite efforts at rehabilitation. Water from these areas is highly acid, and stream channels are a distinctive rust red. The effects of bog iron are detectable for considerable distances downstream from source areas.

The Black Hills are interlaced with an extensive road system; consequently, sediment yield is of concern to watershed management. Although many of the old roads have stabilized since construction, some problem areas are intensified after floods. Trouble spots are steep pitches in grade and channel bottom locations. Two types of areas are especially vulnerable—cohesionless permeable soils that are derived from granite bedrock, and soils that are medium to fine textured, easily compacted, and hence produce large quantities and intensity of runoff.

The undesirable effects of poor locations of old roads have been aggravated with the advent of various types of recreation vehicles. Erosion problems in a few places have intensified as the result of high recreation use. Once such problems are recognized, however, well-established methods are available for stabilization.

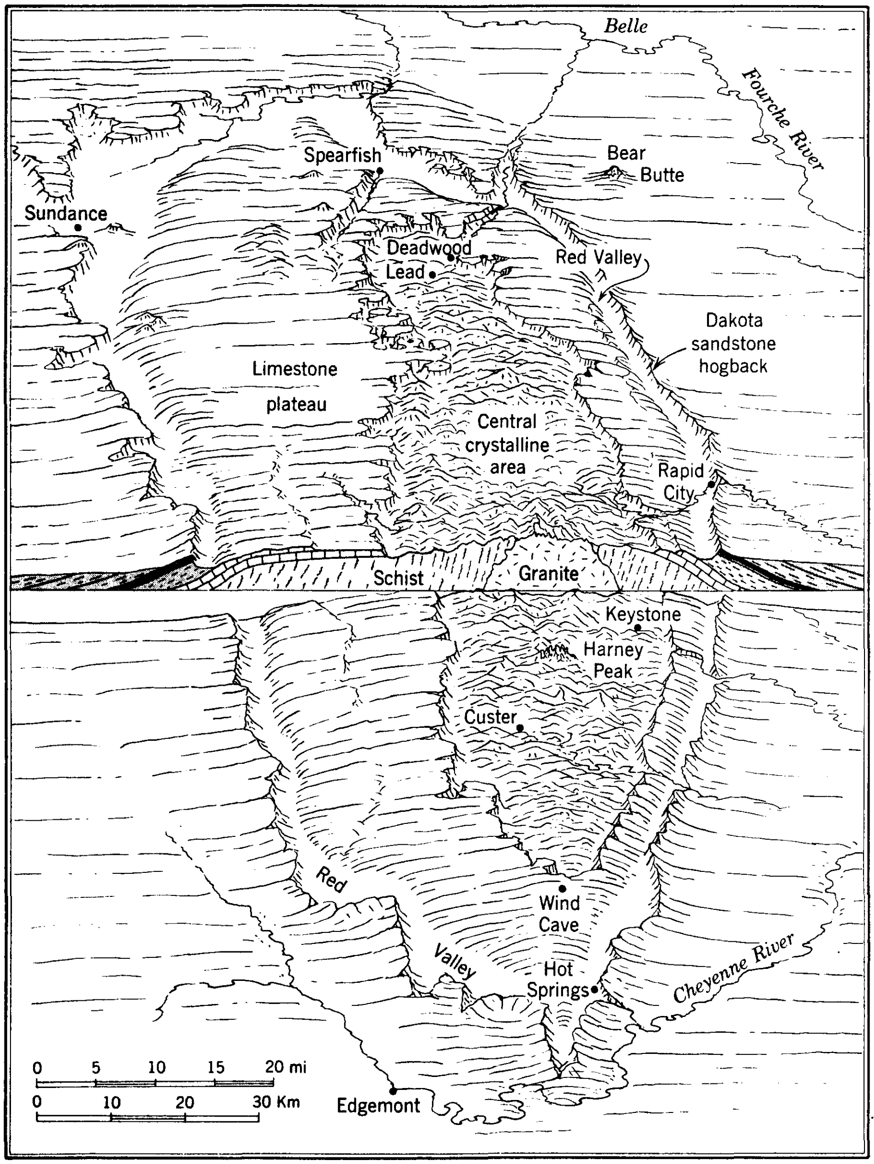


Figure 14.—Geologic map of the Black Hills (from Strahler's Physical Geography, 3rd ed., copyrighted 1969. Reprinted by permission of John Wiley & Sons, Inc., N.Y.).

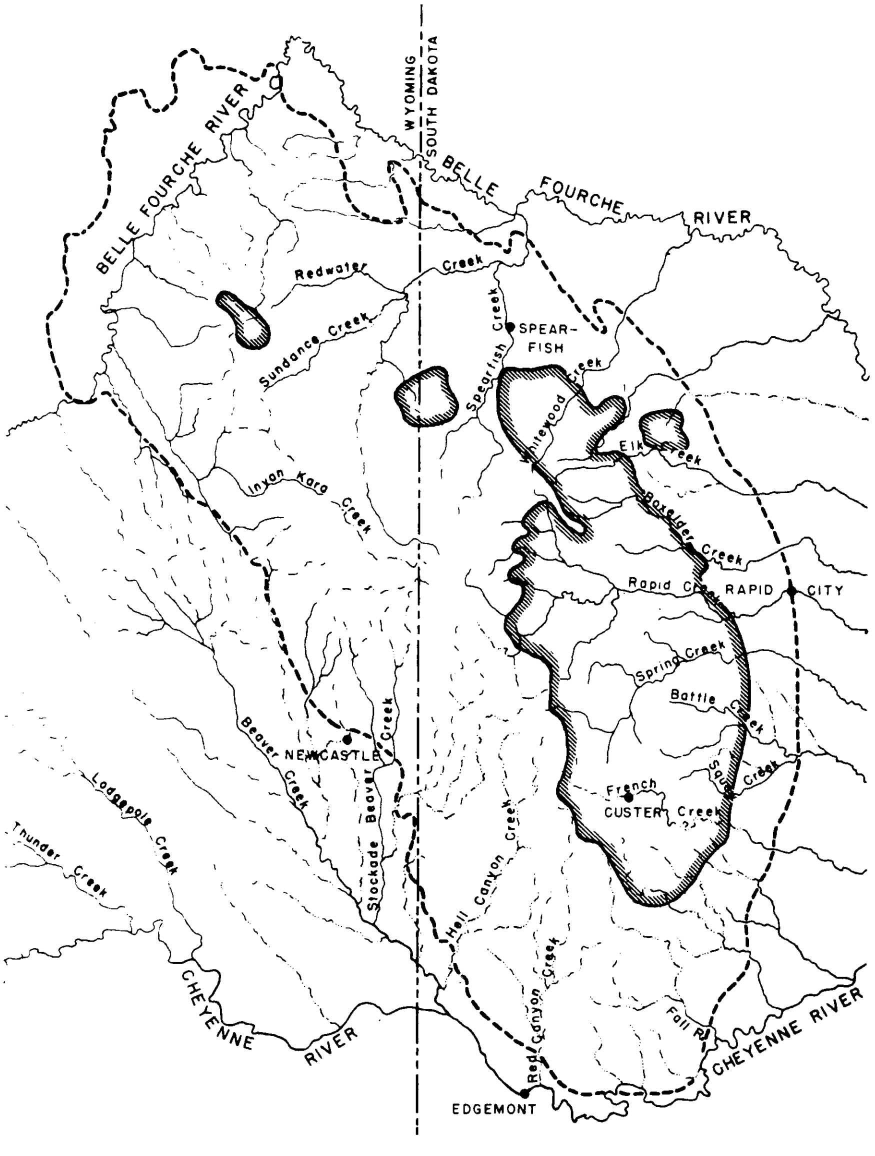


Figure 15.—Drainage map of the Black Hills and Bear Lodge Mountains. The heavy dashed line shows the extent of encircling sedimentary formations. The crosshatched lines show areas of metamorphic and igneous (crystalline) rock formations. Sedimentary formations are found in the remainder of the area.

Geology and Physiography

Geomorphology of the Sturgis watersheds has been carefully analyzed to better our understanding of the hydrology of headwater streams. Morphometric analyses have shown the relative hydrologic importance of several watershed form properties. For example, maximum length of master watershed and the average relief of first-order basins are highly correlated with volume yield and peak flow. Little is presently known about geophysical-hydrologic interactions in small watersheds; work is presently underway to better define soil and geologic properties.

Water-Yield Improvement

Research results from the Black Hills have contributed to the fund of knowledge on water-yield improvement in the central and southern Rocky Mountains. These data support the concept that irregular patchcutting will produce maximum increases in water yields. Small openings on first-order basins and interbasin areas will produce streamflow more efficiently by redistributing the snowpack and reducing consumptive use with minimum watershed and stream channel conveyance losses.

HYDROLOGIC PRINCIPLES IMPORTANT TO MULTIRESOURCE MANAGEMENT OF THE BLACK HILLS

Many of the principles outlined for the subalpine and Front Range zones also apply to the Black Hills. Those that are unique to the Black Hills are summarized below:

- The location of the Black Hills makes them especially attractive to the resident and nonresident public. Accordingly, esthetics are especially important, and water plays a key role. The Hills are an important source of ground water which still has a large untapped potential. Potential surface-water benefits from water-yield improvement exist on forested watersheds upstream from peripheral sedimentary formations. In these areas, irregular patchcutting will produce maximum water-yield increases without causing adverse ecologic effects. Thinnings will result in small or negligible increases in streamflow.

- The advent of recreation vehicles of various types, and the intensive network of old roads in the Hills, have created sedimentation problems in some areas. Most are small and relatively scattered. Where roads are located in stream bottoms or on steep grades, special measures must be taken to insure stability. Because vegetation reestablishes quite easily on most disturbed areas, sediment source areas should not be critical provided that land developments are well engineered and maintained.

- Chemical water quality is a problem in and downstream of a relatively few areas which have been mined for bog iron. Because restoration of such areas is difficult at best and perhaps ineffective, further mining should be discouraged until new methods are developed that will insure site restoration within a short period of time.

WHAT DO WE NEED TO KNOW

Knowledge gaps have been discussed in the previous summaries for the subalpine and Front Range Zones. In addition, there is still a need to adapt existing simulation modeling approaches to Black Hills management problems. To accomplish this, we need additional hydrologic inventory data on soils, geology, runoff, and precipitation to supplement our general knowledge of the area.

The alpine zone (fig. 16) is that area above tree line which varies from about 10,000 feet in southern Wyoming to about 12,000 feet in southern Colorado and northern New Mexico. Estimates vary, but it is generally believed that alpine areas occupy more than 5 million acres in Colorado and Wyoming—about equally divided between each State—and about 250,000 acres in Utah.

The primary vegetation is composed of grasses, sedges, and a wide variety of forbs and lichens. Tree species reflect local soil-moisture conditions, and include dwarf willow, spruce, fir, and an occasional limber or bristlecone pine. Stunted, malformed coniferous trees occur in streamlined clumps at timberline. Wind-exposed ridges support only prostrate plants and cushion-type forbs and lichens. Terrain depressions on lee slopes accumulate blowing snow. Here, vegetation may be dense willow thickets in boggy areas, or nothing more than a few snow-tolerant forbs where snow accumulates to great depths.

WHAT WE KNOW ABOUT ALPINE HYDROLOGY

Landforms, Climate, and Streamflow

Landforms depend to some extent on bedrock geology, and vary from broad, gently sloping ridge crests and plateaus to steep and rugged peaks. Extensive glaciation has played a significant role in shaping the topography. Mass soil movement, patterned ground, and soil frost are also prevalent features.

Persistent winds and cold temperatures mark the climate of the alpine zone. Summer temperatures rarely exceed 70°F, and subzero days are common in winter. Over 75 percent of the annual precipitation occurs as snow, which is moved from exposed areas to wind-protected locations. Snow accumulates all winter and melts in early spring to early summer. The summer rainfall regime is similar to that in the subalpine zone.

Runoff data are scarce because few streams have been gaged in the rather hostile and inaccessible alpine environment. Estimates vary from 23 inches in Alberta, Canada, to 54 inches in Colorado. On the average, streamflow peaks in early summer, producing about 85 percent of the annual flow between May 1 and July 31. Less than 5 percent of the total flow occurs between December 1 and March 31.

Figure 16.—The alpine zone in the vicinity of Berthoud Pass, Colorado.

Alpine drainages with more late-lying snowfields produce the most late-summer streamflow. Moreover, evaporation losses are low, so that watershed efficiencies (runoff expressed as a percentage of net input) can approach 90 percent during most years. Snowmelt runoff from alpine drifts produces surface runoff and contributes to water which is stored in fractured rocks deep within mountain massifs.

Alpine Snow Accumulation

Snow first accumulates at the windward edge of most fields and builds downward, rather than by initially filling in the deeper parts. The size and shape of the fields reflect the size and shape of barriers behind which they form, with the exception that very heavy or very light snow years make a difference in the size of the field. Some accumulation areas are not completely filled during dry years.

Most of the winter snow accumulates from a relatively few events. Between 55 and 70 percent accumulates during the 5 weeks of heaviest drifting, with between 30 to 40 percent accumulating in the 2 weeks of heaviest drifting. Generally, the first major storm of the season is also the largest snow accumulation period.

Evaporation, Condensation, and Melt

The onset of ablation varies from year to year in response to topography, the amount of snowpack, and spring weather conditions. Once spring melting is firmly established, the reduction in snowfield area progresses at a remarkably uniform rate, regardless of when the snowmelt season begins or the initial amount of snow.

In most cases, moisture exchange between the snow surface and overlying air is between 2 and 3 percent of the daily melt. Condensation dominates the nights and evaporation the mornings. Net losses in moisture generally occur in July, whereas net moisture gains can be expected in August. Carbon black, soil, sawdust, and gravel all affect snowmelt rates. Sawdust can retard melt, whereas carbon black will accelerate snowmelt, provided that it is applied evenly and in a thin layer.

Water-Yield Improvement

Extensive research under winter and summer conditions has shown that one feasible technique for improving water yields from the alpine zone is to build snowfences upwind of natural accumulation areas. The resulting increased snowpack, held in deep, high-elevation drifts that persist until late summer, will affect runoff. By trapping snow which would normally be lost to the atmosphere or blown into the subalpine zone below, streamflow timing is changed so that some runoff normally produced during the spring freshet is diverted to periods of low flow. The primary effect is to change the distribution of runoff, rather than to increase water yield.

Snow Accumulation

Studies of snowfence design features have shown that fence effect varies greatly with size of gap, and fence height and density (fig. 17). Relations have been established between gap size and the location and size of the lee drift. These are presented in Martinelli's detailed status-of-knowledge summary (RM-138).

Topography also exerts an important effect on fence performance. Pressure-gradient concepts provide a rationale for relating fence and terrain effects to snow accumulation. While pressure does not change in the lower layers for airflow over flat surfaces, irregular terrain or natural and artificial barriers will produce local pressure gradients. A favorable gradient (high pressure to low pressure) exists when air flows uphill, whereas an adverse gradient (low pressure to high pressure) exists when air flows downhill or against a barrier. Velocity and shear stresses in the lower layers increase downward, and maximum shear stress is at the surface along a favorable pressure gradient. Along an adverse gradient, velocity and shear stresses near the ground decrease and maximum shear stresses move up from the surface. The carry-

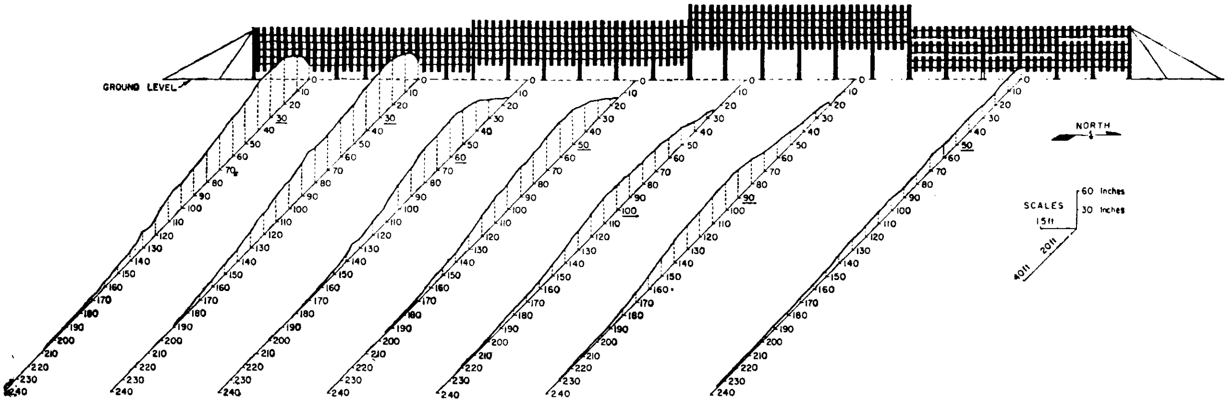


Figure 17.—Typical snowfence panel and snowdrift pattern at Pole Mountain, Wyoming. Snow depths of four locations. Right panel swings open in high winds; others are tests of bottom gap size. Note: There are three different scales in the diagram.

ing capacity of wind is directly related to the shear stresses in the lower layers. Accordingly, in an adverse gradient situation, velocities and shear stresses are reduced so that transported snow settles out of the airstream. Examples of how the above concepts help to explain total snow accumulation and maximum drift length observed in several typical terrain situations are presented in the comprehensive summary (RM-138). Five cases are discussed which include:

A snowfence on a uniform windward slope.
A snowfence on a uniform leeward slope.
A snowfence located leeward from a rounded ridge crest.
A snowfence at a sharp ridge crest.
A fence located at a break from horizontal to lee slope.

A method for estimating drift volume as a function of slope, fence density, and size of gap is also presented.

Snowmelt and Runoff

At the most efficient fence sites, approximately 60 to 120 feet of fence has a potential for producing an extra acre-foot of water at the start of the melt season. This holds for fences 10 to 12 feet tall, 40 percent fence density, bottom gaps of 2 to 4 feet, and snow density in the lee drifts of 500 kilograms per cubic meter. At such sites, the melt season is prolonged approximately 1 to 3 weeks. In general, an extra 2 feet of snow depth on July 1 increases the insuing melt season by 1 week.

PRINCIPLES IMPORTANT TO WATER-YIELD IMPROVEMENT IN THE ALPINE ZONE

- Ten years of study have shown that the best sites for increasing the amount of snow in alpine drifts will have: (1) ridge crest locations with the deep part of the natural drift not more than 8 to 10 times fence height to the lee, (2) upslope or level windward approach, (3) good orientation to prevailing drifting winds, (4) upslope or level terrain to the lee of the accumulation area, (5)a contributing distance upwind of the fence of at least 500 feet, (6) little natural accumulation upwind of the fence, and (7)adequate protection from direct solar radiation.

- Poor sites for snowfences have: (1) a downslope approach to the fence, (2) no natural catchment within 8 to 10 fence heights downwind of the logical fence location, (3) upwind accumulation sites to intercept snow or to throw a drift on the fence, (4) variable wind direction during drifting, and (5) a steep downslope exhaust zone that results in reverse windflow and erosion of the lee deposition.

- The following pressure-gradient concepts apply: (1) snowfences that obstruct flow in a favorable pressure gradient yield smaller and shorter drifts than expected over horizontal terrain, (2) the effects of fences located at the change from a zero or favorable to adverse pressure gradient should increase as the gradient increases up to the point where reverse flow in the eddy begins to erode the downstream edge of the drift, and (3) fences located within an average pressure region should show effects that follow those in the preceding statement, but the fences usually become buried in the drift.

- Details of snowfence construction, developed from long experience, present guidelines for structural stability, density, and gap width. The unique function of these structures, and the loads which they must withstand, require application of sound engineering principles to insure an adequate fence system.

- Snowfences also have a high utility for uses other than increasing late summer flows. Fences can help solve special problems, including avalanche control, highway and parking lot protection, wildlife habitat enhancement, and agricultural and domestic water development. Fence location, density, bottom gap, and height all vary, depending on the objective.

- Fences should be carefully located in alpine areas. They should not be placed indiscriminately along entire ridges. Visual impact should be minimized by careful design and use of materials which tend to blend in with the natural landscape.

- Use of snowfences for water-yield improvement from alpine areas should be considered as supplemental to other watershed management practices in forested or riparian zones. All hold promise for providing needed solutions to future water supply problems.

WHAT DO WE NEED TO KNOW

Several knowledge gaps must be filled before complete guidelines for snowpack management in alpine and other areas can be developed. First, we must be able to determine the mass flux of snow being transported past a given site to determine snow trapping efficiency. Particle counters will help to solve this problem. Secondly, we need better information on the combinations of terrain features which produce optimum snow accumulation sites. The pressure gradient concept is a promising way of developing initial criteria based on sound physical principles. Finally, more data are needed to further refine theoretical models which predict sublimation losses from blowing snow.

Other techniques should be explored for improving the timing and amount of water yield from the alpine zone. These include: (1) terrain modification, (2) intentional avalanching, and (3) artificially creating massive accumulations of ice from winter streamflow.

THE BIG SAGEBRUSH ZONE

Big sagebrush occupies almost 200 million acres in the 11 western States. Three subspecies—basin big sagebrush, Wyoming big sagebrush, and mountain big sagebrush—are recognized. Identification of big sagebrush to the subspecies level is important, since subspecies often indicate significant environmental characteristics of the site. Mountain big sagebrush typically grows above 7,000 feet on lands which receive a large proportion of the annual precipitation as wind-deposited snow. This subspecies affords a higher potential for water-yield improvement than does Wyoming big sagebrush, which grows below 5,000 feet on sites with less soil development and precipitation.

Sagebrush adapts to particularly dry conditions by shedding or reducing the size of its leaves to maintain a favorable internal water balance. Its root system enables big sagebrush to be a vigorous competitor for nutrients and soil moisture. The largest mass of roots is in the upper 2 feet of soil. When moisture has been depleted from the surface layers, its lateral and tap root systems are capable of utilizing water to depths that sometimes exceed 6 feet.

WHAT WE KNOW ABOUT BIG SAGEBRUSH HYDROLOGY

Climate and Water Yield of Mountain Sagebrush

The climate of the big sagebrush zone is characterized by a relatively warm and dry growing season where most of the precipitation is received as snow. Annual precipitation in the mountain big sagebrush zone is 15 to 20 inches per year, and approximately 9 to 12 inches of this total falls as snow. Snow does not melt during the winter months except in the lower portion of the zone on slopes that have a high energy input from solar radiation. Snowmelt generally begins in April or May. About 60 percent of the warm-season precipitation falls during June and September. Because of the combination of small storm size and high evaporation rates, most rainfall during July and August is ineffective in replenishing soil moisture. June rainfall is utilized by growing plants, whereas September rainfall begins to increase soil moisture levels.

Limited data collected at two research locations indicate most summer storms are small. Two-thirds of the rainfall events produce 0.10 inch or less. The duration of rainfall in excess of 1 inch per hour is usually less than 10 minutes, and average intensity for the entire storm period generally is less than 1 inch per hour. However, infrequent high-intensity thunderstorms can generate high rates of runoff and associated erosion.

Hydrologic data from mountain sagebrush are sparse. Annual precipitation of 15 inches produces approximately 3 inches of streamflow. Runoff during the snowmelt season is extremely sensitive to weather changes. The highly variable depth of snow accumulation on a watershed, and watershed orientation, also contribute to the volatile character of snowmelt runoff. Another phenomenon recently observed on sagebrush watersheds is "over-the-snow" flow (fig. 18), caused by a well-developed drainage network on top of dense snow in high accumulation areas. Figure 19 compares the snowmelt hydrographs from three watersheds representative of the mountain sagebrush type.

Figure 18.—Water flowing over the snow surface produced this channel into the dense snow filling a tributary. Such channels quickly route melt water with minimum conveyance losses. Dark material on the sides and bottom of this channel is soil deposited by runoff.

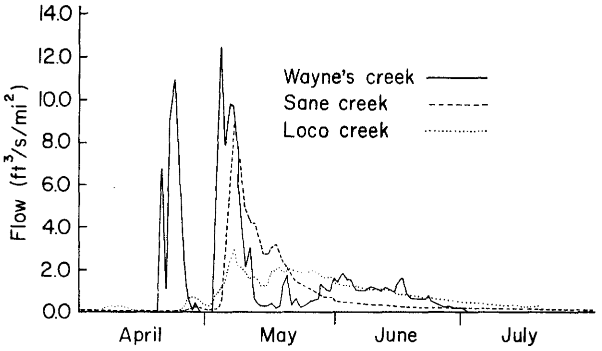


Figure 19.—Snowmelt runoff from the sagebrush type is sensitive to daily weather changes as shown by flow on Wayne's Creek, near Dubois, Wyoming. Water flowing on top of the snow caused high discharge rates on Sane Creek, near Saratoga, Wyoming, compared to those of Loco Creek, an adjacent watershed that did not develop "over-the-snow" flow.

Although telltale signs of severe runoff and erosion from intense rainfall have been observed, there is not yet enough information to completely define summer precipitation and runoff characteristics. Thirteen years of data from a 60-acre high-elevation drainage basin suggest that most high runoff events are caused by rain falling on premoistened soil rather than in response to high-intensity thunderstorms. It is reasonable to assume that infrequent flooding phenomena in the Black Hills, mountain sagebrush type, and Colorado Front Range are similar in nature.

Wind and Drifting Snow

One of the most distinctive features of the mountain sagebrush type is persistent wind, which significantly affects snow accumulation. Much of the snow is blown from windward slopes and ridgetops to protected areas on the lee side of ridges or into incised drainages. The threshold speed for transport of newly fallen snow is approximately 12 miles per hour; metamorphosed snow requires higher speeds. Although unknown but significant quantities of snow are sublimated, the remainder commonly accumulates in drifts 10 to 20 feet deep. This concentration of snow and subsequent ground water recharge results in springs and perennial streamflow from sagebrush lands (fig. 20). The magnitude of evaporation from the snow surface, and from moistened soil during melt is not known. Present indications are that it could comprise as much as one-half of the water volume for isolated drifts.

Watershed Management

Sagebrush Control

Sagebrush conversion is one of the primary tools utilized by range managers to increase forage for cattle and sheep. Burning was an early means of conversion, and is still effective. Plowing or disking is also effective, but limited to moderate slopes without numerous rocks. The discovery of phenoxy herbicides resulted in widespread use of 2, 4-D in the management of big sagebrush lands. Spraying has been the preferred method of sagebrush control since the early 1950's. Sprayed acreage in Wyoming increased from 319,000 acres in 1962 to between 1.3 and 1.4 million acres by 1970. This trend is indicative of sagebrush control practices throughout the West. Reseeding is a necessity in conjunction with control methods that destroy all vegetation, and is also recommended, regardless of the control method, where desirable plants comprise less than 20 percent of total original plant cover.

Native grass production commonly doubles immediately after sagebrush removal, and may triple that of unsprayed areas within 3 years (fig. 21). However, the level of increased production that can be expected over the long term has not been adequately established. Recent evidence indicates that production increases may persist for 15 to 30 years after conversion. The rate of sagebrush invasion after treatment depends most on the degree of initial brushkill and subsequent grazing

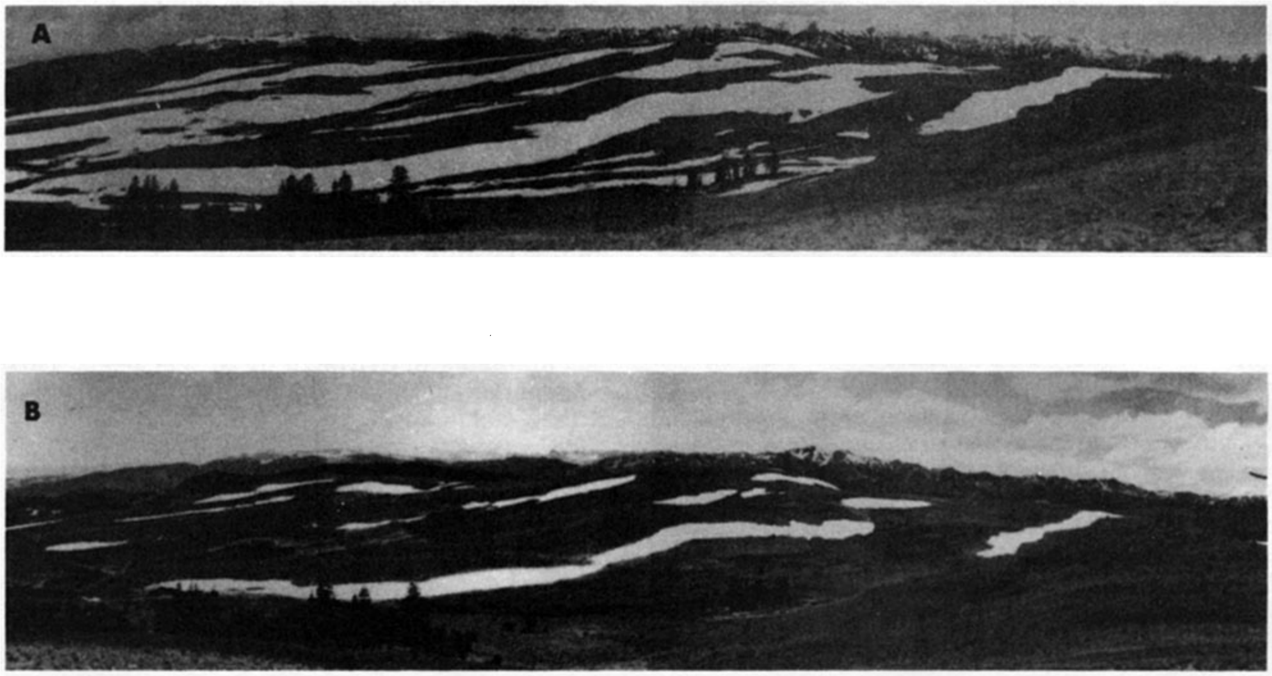


Figure 20.—Deep drifts persist long after the bulk of the snowpack has melted: **A**, snow conditions June 3, near the time of peak streamflow; **B**, snow conditions June 16, about 1 week after the hydrograph peak.

management. Uncontrolled grazing will generally result in rapid reinvasion, but with conservative grazing practices, the increased level of grass production will persist for a number of years, and the full benefits of sagebrush conversion can be realized.

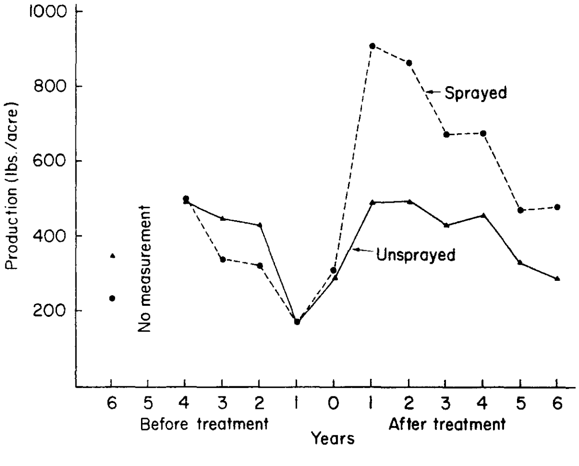


Figure 21.—Grass production (air-dry) for a sprayed and adjacent unsprayed high-elevation sagebrush watershed.

Burning, and mechanical methods that do not destroy the herbaceous vegetative cover, have little effect on herbaceous composition after treatment. Spraying strongly favors grasses over forbs, however. Spraying will drastically diminish forb production, and recovery is generally slow. Forb damage, a byproduct of spraying, should be carefully weighed against the benefits of increased grass production. Forbs are an essential ingredient in the diets of young sage grouse, and they are also sought by cattle.

The net effect of spraying on herbaceous vegetative composition depends upon the proportion of grasses and forbs in the sagebrush stand. If forbs comprise a substantial portion of untreated vegetation, much of the grass response takes place at the expense of forbs. Big sagebrush control will reduce total above-ground biomass production, even though combined grass-forb productivity may increase substantially after treatment. About one-third of the vegetative matter in climax stands is big sagebrush, but on sites where it is sprayed as a range improvement practice, young sagebrush may contribute two-thirds or more of the annual production. The fact that the increase in herbaceous production does not fully replace sagebrush herbage indicates a diverse mixture of life forms more fully utilizes site resources than does a limited number of species or life forms.

Soil Moisture

The conversion of a mountain sagebrush stand to herbaceous vegetation reduces soil moisture withdrawal about 15 percent. This difference takes place while vegetation is actively growing, and not uniformly through the summer season. After midsummer, the rate of use is similar for both treated and untreated vegetation (fig. 22). Soil-water use declines sharply on treated areas when herbaceous vegetation reaches maturity, and after the midsummer leaf drop by big sagebrush in sagebrush stands.

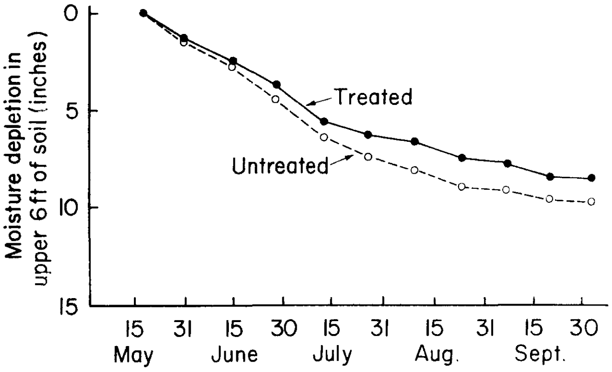


Figure 22.—Sagebrush conversion reduces soil-water use about 15 percent during the time of active vegetation growth. The rate of use after midsummer is similar for both treated and untreated vegetation.

The root systems of big sagebrush are capable of extracting water deep in the soil after moisture near the surface is depleted. Accordingly, about 80 percent of the water savings takes place at depths between 3 and 6 feet when sagebrush is removed. Moisture to support herbaceous vegetation on treated land is derived mainly from the top 3 feet of soil. Soil-water use in the surface 2 feet equals or exceeds that of undisturbed sagebrush vegetation. Some soil moisture is used by both treated and untreated vegetation until late fall. Once snow begins to accumulate, however, soil-moisture content does not change through the winter months.

Snow Accumulation

Sagebrush plants trap snow since the leaves and twigs promote snow deposition by reducing windspeed. Live sagebrush plants, and the skeletal remains of sprayed plants, are more effective snow-trapping agents than herbaceous vegetation. Snow accumulates faster in sagebrush than grass stands as long as the brush remains above the snow surface.

Sagebrush control reduces snow accumulation most strongly on windward slopes and to a lesser extent on leeward slopes. Sagebrush removal may reduce the rate of accumulation early in the winter, before vegetation is covered, but have little effect on final depth where natural snow deposition exceeds the height of sagebrush. Snow accumulation is governed by the interaction of the wind with topography once vegetation is covered. Sagebrush removal can affect snow deposition at a given point, but may not affect total storage on a watershed since large-scale snow accumulation is governed more by topography than by vegetation.

Streamflow

Results from one paired watershed study in mountain sagebrush suggest that total annual water yields can be increased approximately 13 percent by converting the shrub-dominated vegetation to a herbaceous type. While these results are not statistically significant at the 95 percent level of confidence, the apparent increase in water yield closely approximates measured differences in soil moisture withdrawal. Accordingly, the streamflow increase suggested by watershed comparisons is probably a real response. Treatment has no effect on the yearly maximum discharge rates, mean daily discharge rates, or recession flows in summer.

The 13 percent streamflow increase is considered to be about maximum for the big sagebrush type, and is attained only: (1) on sites where there is significant precipitation to rewet the soil throughout its profile, and (2) where the soil mantle is sufficiently thick so that the rooting zone of replacement vegetation lies above the deep root system of the sagebrush which formerly occupied the site.

Blowing Snow Control

Snow transported by wind is subjected to large sublimation losses. Snowfences, previously discussed, can also be effectively used in sagebrush and grasslands to reduce sublimation, and thereby tap this heretofore unavailable water source. A mathematical model has been developed to determine the quantity of water equivalent that sublimates while snow is being transported by wind. This model assumes that the annual volume of sublimated snow is a function of: (1) the mean annual snow transfer coefficient, or the ratio of the quantity of snow transported by wind to that which falls during the winter drift period; (2) mean winter precipitation received during the time snow is subjected to drifting; and (3) the average distance a snow particle travels before sublimating(transport distance) during the winter drift period.

In southcentral Wyoming, the snow transfer coefficient is approximately 0.7 for mountain big sagebrush 8 to 16 inches tall. This means that 70 percent of the precipitation that falls during the drifting season returns directly to the atmosphere when no barriers exist to induce snow deposition. The residual 30 percent is stored in the crown space, which protects the snowpack from wind. Average transport distances vary from 3,300 feet at a 7,500-foot elevation to 5,000 feet at the 8,500-foot level. These large distances, and a drift period which extends from November 1 to March 30, suggest a high potential for exploiting this drifting-snow resource with minimal impact on the environment and other land uses. Snowfences properly located provide an effective means to capture and retain wind-borne snow with high efficiency (fig. 23). Engineering guidelines are available for determining proper fence size and spacing. Specific design criteria and references to pertinent literature are found in the comprehensive status-of-knowledge summaries (RM-138 and RM-140).

Erosion and Sediment Yield

There is general agreement that watershed cover—including litter, rock, and live vegetation—is an important factor influencing infiltration, erosion, and subsequent sediment yield. From the standpoint of watershed management, practices that increase litter and vegetation promote soil stability.

Little factual information on sedimentation from big sagebrush lands is available. Measurements on two areas in Wyoming suggest that both suspended sediment and bedload movement are typically low. High sediment movement occurs only during extreme precipitation events. The over-the-snow flow phenomenon previously discussed, may also increase sediment movement.

Sagebrush-conversion techniques which minimize soil disturbance are preferred. Spraying will produce the least soil disturbance. Plowing should be used only when there is a high likelihood of establishing a seeded stand quickly.

HYDROLOGIC PRINCIPLES IMPORTANT TO MULTIRESOURCE MANAGEMENT OF THE BIG SAGEBRUSH ZONE

- More than 90 percent of big sagebrush vegetation is killed by burning, mechanical removal, or chemical herbicides, when these techniques are properly implemented. Reseeding is recommended on sites where the population of desirable species is depleted, and must accompany those methods which destroy all vegetation.

Figure 23.—Windborne snow that otherwise returns to the atmosphere can be trapped and stored behind snowfences. There is an opportunity to improve water yield wherever a large quantity of snow is transported by wind.

- The composition of herbaceous vegetation is largely unaffected by burning or mechanical sagebrush control methods which leave existing herbaceous cover intact. Spraying, however, can reduce forb production 45 to 65 percent. Forb damage caused by spraying with phenoxy herbicides should be carefully weighed against increased grass production, since forbs constitute an important food source for certain wildlife species as well as livestock. The land manager controls plant composition when reseeding is necessary following sagebrush removal. Planted species can be selected to optimize vegetation composition to meet specific management objectives.

- Grass production commonly doubles after spraying, but declines with time as sagebrush gradually reoccupies the site. The duration of treatment effect is strongly influenced by grazing management practices following sagebrush control. Most projects probably have an effective life of between 15 and 30 years, if initial sagebrush kill is high and conservative grazing practices are followed.

- The production of above-ground herbaceous biomass (including production by sagebrush) is reduced by sagebrush removal. While combined grass-forb production can increase approximately 50 to 200 percent, this is not sufficient to replace the herbage produced by the original sagebrush. When sagebrush is sprayed, forbs as well as sagebrush are killed, so that part of the grass response simply compensates for decreased forb growth.

- Techniques which cause the least soil disturbance are recommended for converting big sagebrush to a herbaceous vegetation type. Plowing or disking should be restricted to lands with little natural erosion and where there is a high probability of establishing a seeded stand quickly. A high erosion potential also exists after sagebrush stands are burned until residual vegetation regrows sufficiently to provide soil protection.

- Soil-moisture withdrawal can be decreased approximately 15 percent by sagebrush removal (1) if the rooting depth of residual vegetation is less than that of the sagebrush which formerly occupied the site, and (2) if snowmelt is sufficient to recharge the entire soil mantle. Soil-moisture use is reduced at depths greater than 2 feet and during the time that vegetation is actively growing. Water use in the surface layers of soil is unchanged or may increase, since treatment shifts the rooting zone to the upper part of the soil profile.

- The interaction of wind with vegetation and topography controls snow deposition. Live sagebrush crowns which protrude above the snowpack collect snow more efficiently than do defoliated sagebrush crowns or herbaceous vegetation. Sagebrush removal can reduce snow accumulation on windward slopes; basin-wide snow storage may not be significantly affected, however, since wind and topography are the primary factors controlling snow accumulation.

- Indications are that annual runoff from mountain sagebrush can be increased a maximum of 15 percent through extensive sagebrush eradication. Again, water yield can be increased only when rooting depths of replacement vegetation are less than the original sagebrush, and snowmelt exceeds soil-water recharge requirements. Treatment apparently does not affect peak or recession flows appreciably.

- Drifting snow represents a large, untapped water resource on sagebrush and grasslands. As much as 70 percent of this snow is lost to the atmosphere under natural conditions. Snowfences provide an efficient means of capturing drifting snow with little impact on the environment or other uses of the land. Snowfences can be used to develop water sources or to augment existing supplies; however, sublimation and evaporation can extract as much as 50 percent of the water stored in isolated drifts behind snowfences.

WHAT DO WE NEED TO KNOW

More documentation is needed on the long-term effectiveness of sagebrush removal, particularly after spraying, since the majority of sprayed land has been treated during the past 15 years. Range management practices that utilize the increased grass production most efficiently also need to be determined.

The factors that govern infiltration and sediment movement are complex and their interrelationships are poorly understood. More research is needed to identify those soil, cover, topographic, and hydrologic parameters which determine infiltration and erosion. Perhaps the biggest knowledge gap is the lack of direct measurements of bedload and suspended sediment for any length of time in sagebrush lands.

Present techniques for gathering such basic hydrologic information as the quantity of winter precipitation, the flux and timing of snow relocation, and storage of water as snow on a watershed, are not adequate. Shortcomings of current winter precipitation measurement techniques on windswept sagebrush lands are especially acute. An unshielded standard 8-inch precipitation gage may catch only one-third of precipitation received as snow in a location exposed to the wind, and about two-thirds of true precipitation if shielded.

In windswept regions, effective watershed precipitation is composed not only of that precipitation falling on the area, but also of the net transport of water in the form of windblown snow onto or off the watershed. Snow relocation becomes an increasingly important process in determining effective winter precipitation as the size of the drainage decreases, and must be considered for precise water-balance calculations. The total flux of snow transport cannot be adequately measured at the present time. Instruments are available to measure the flux at a given point, but instrument systems to integrate total flux in the atmosphere have not been developed.

Low-cost, rapid techniques to quantify the volume of snow stored on a watershed as well as its density are needed. Snow accumulations that vary from a few inches to many feet typify big sagebrush watersheds, particularly at higher elevations in the zone. The presently available, on-the-ground survey methods are inadequate when measuring snow volume on entire watersheds.

The magnitude and importance of various energy sources that contribute to snowmelt in the big sagebrush environment are poorly understood. The contribution of advected energy to the snowmelt energy budget, for example, is unknown. It probably becomes increasingly important since large portions of the watershed lose their snowcover early in the melt season. Thereafter, air warmed by passage over snow-free areas moves across the remaining snowfields. Also, snow in the major accumulation zone may persist for several months after the general snowpack has melted. Advected energy is undoubtedly an important constituent in the energy budget of late-lying drifts, but its influence should also be established for areas of shallower snow.

Progress has been made in adapting a dynamic hydrologic simulation model to the big sagebrush type. Once this model is adapted, it will provide a useful tool for making objective predictions of changes in water yield that can occur when different watershed management practices are imposed on big sagebrush lands. Coupling this model with the model for predicting snow transport would result in a powerful system for comprehensive analyses of big sagebrush hydrology and watershed management alternatives.

Leaf, Charles F.
1975. Watershed management in the central and southern Rocky Mountains: A summary of the status of our knowledge by vegetation types. USDA For. Serv. Res. Pap. RM-142, 28 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

Summarizes a series of comprehensive reports on watershed management in five major vegetation zones: (1) the coniferous forest subalpine zone; (2) the Front Range ponderosa pine zone; (3) the Black Hills ponderosa pine zone; (4) the alpine zone; and (5) the big sagebrush zone. Includes what is known about the hydrology of these lands, what hydrologic principles are important for multiresource management, and what additional information is needed for each vegetation type.

Keywords: Watershed management, land use planning, alpine hydrology, range hydrology, snow hydrology, blowing snow management, water yield management.

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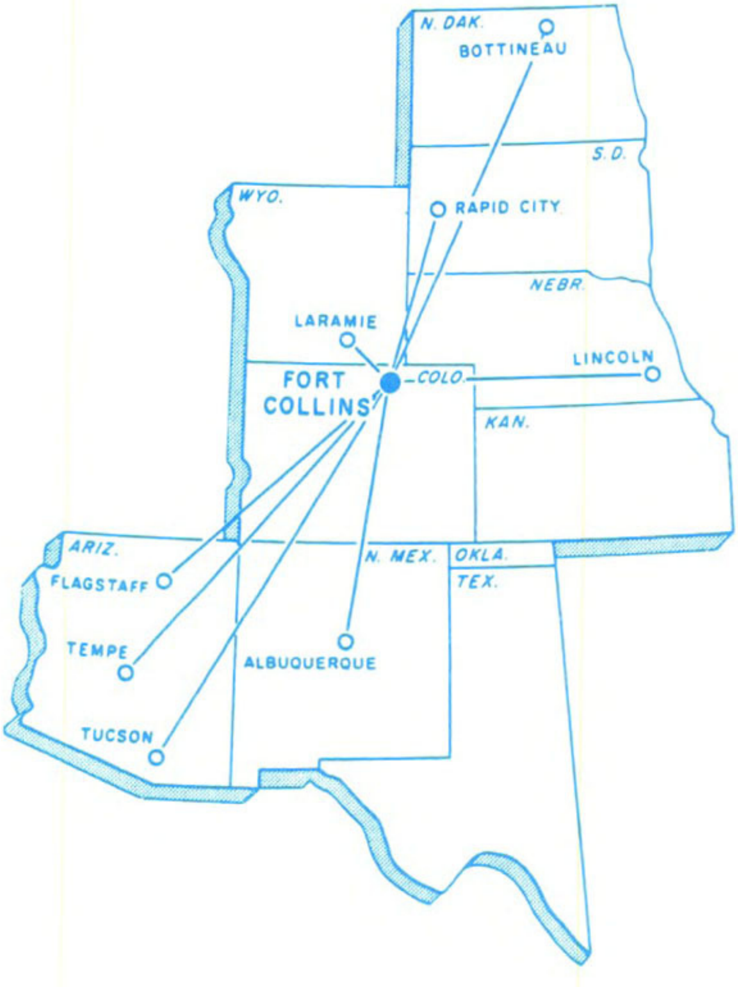

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