WATER YIELDS THROUGH WATERSHED MANAGEMENT IN NEW MEXICO

by

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Climate and water supply have exerted a powerful influence in the settlement and development of New Mexico. The high mountains have adequate precipitation for agriculture and the lower plains and valleys with deep fertile alluvial soils, long growing seasons and high temperatures are favorable for growing crops. Yet, precipitation is wholly deficient in these lower-lying lands. Thus, the problem in this state has been and will continue to be -- how best to manage, conserve, protect, store and deliver the mountain water supplies to the lower water-using areas.

The recent upsurge in population with its increased water-use and the prolonged drought starting in 1943 have resulted in an increased demand for water. This increased demand is causing a diligent search for new supplies and for an answer to the age-old question of how much more water can be obtained from existing sources. It is, therefore, natural that we should look to the mountains and wildlands with its myriad of small watersheds and ask the question, "How can these lands provide more usable and dependable water for downstream use?"

Our knowledge of the relation of climate, topography, geology and soil on streamflow, water yield and soil erosion as affected by type, condition and use of vegetation is mostly dependent on research findings outside of New Mexico. The most pertinent study areas are shown in figure 1. These are briefly described.

EXPERIMENTAL STUDY AREAS

The Sierra Ancha Experimental area is a group of variable-sized watersheds that form part of the Salt River drainage. It is located in the Sierra Ancha Mountains above Roosevelt Reservoir in central Arizona. This is an outdoor laboratory with facilities available for measuring individual plant and soil changes under controlled conditions as well as changes taking

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place through different methods of management on natural watersheds. Small plots and lysimeters range in size from a few feet to 1000 square feet. Findings obtained from lysimeters and plots are progressively applied to small and then large natural watersheds (*38*). 2/

The Fraser Experimental Forest lies west and north of Denver near the Continental Divide (*25*). Water supply is the most important subject of research. About half of the annual precipitation is water yield from these forested watersheds in lodgepole pine and spruce-fir. Since 70 percent of the water yield comes from melting snow, research in watershed management has dealt mainly with the hydrology of snow and the influence of vegetation on snow accumulation and disappearance. Plots and natural watersheds are used in going studies.

At Manitou Experimental Forest in the Colorado Front Range, west of Colorado Springs, research has been concerned with water yield from ponderosa pine watersheds and the influence of grazing in parks and grassy openings on runoff and erosion (*26*).

The San Luis watersheds in New Mexico are to be used in a study designed to evaluate the effect of grazing and land treatment on surface runoff and sediment production in the high silt producing zone of the Rio Puerco. The U. S. Geological Survey, Bureau of Land Management and the Rocky Mountain Forest and Range Experiment Station are cooperating in this endeavor. The Geological Survey Cornfield Wash study is located 6 miles to the west and includes measurement of precipitation, surface runoff and sediment.

The Pine Flat study area involves the measurement of soil moisture depletion and accretion under pinyon trees, in an opening mostly blue grama and on a plot in this same opening kept bared of vegetation.

On Montano Grant, west of Albuquerque, precipitation and surface runoff have been measured continuously from 3 small semidesert watersheds for a period of about 15 years. The study was started and maintained by the Soil Conservation Service until recent years, when it was transferred to the Agricultural Research Service.

The first important watershed investigation in the United States was started during 1909 at Wagon Wheel Gap, Colorado in our own Rio Grande Basin. It was concluded in 1926. The final report (*2*) has now become a classic in watershed literature.

2/ Italic numbers in parentheses refer to literature cited.

Streamflow, precipitation, sediment and other related factors were continuously measured for 15 years on two small (212 and 222 acre) watersheds near Wagon Wheel Gap in the San Luis section of the Rio Grande. Both watersheds were left undisturbed for the first eight year period, then, one of the watersheds was cut of practically all woody vegetation and records continued for another seven years. The publication of the basic data affords the fullest opportunity to make independent analyses. This has been done by other investigators (19) and although some controversy was raised, it added to the validity of the interpretation and conclusions reached in the original report.

WATER PRODUCTION ZONES

New Mexico may be divided into three main water yielding zones on the basis of precipitation and evapo-transpiration potential. Fletcher and Rich (14) using the method developed by Thornthwaite (35) classified New Mexico lands according to this water yielding potential, figure 1. The high water yielding zone is in the mountains and is mostly forested while the low water yielding zone comprises grassland and shrub in the lowlands. An intermediate water yielding zone, mainly, ponderosa pine and pinyon-juniper woodland, lies between these other 2 extremes.

The graphic relation of precipitation to maximum water use by vegetation for high, intermediate and low elevations has been presented for 3 stations (Wagon Wheel Gap, Colo.; Santa Fe and Albuquerque, New Mexico) in the Upper Rio Grande Basin (11). The Wagon Wheel Gap station represents conditions in the high mountains of north-central and northwestern New Mexico. Water surplus exists during the seven month period, October through April, while in Albuquerque, a lowland station, there is a surplus of water only during the two coldest months -- December and January. The station at Santa Fe represents the lower-elevation pinyon-juniper woodland, an intermediate point. At this location, water surplus is insufficient to satisfy soil moisture deficit and water yield is low. Precipitation distribution is similar at all 3 locations with the exception that March and April receive appreciable quantities at Wagon Wheel Gap. The times of water use are also similar, highest in the summer and lowest in the winter. Fletcher and Rich (14) have shown there are four distinct periods: water surplus, water deficiency, soil moisture utilization and soil moisture recharge. Only at Wagon Wheel Gap can we expect a water surplus in excess of soil and watershed storage.

This method of classifying water_yielding zones compares favorably with the direct method of mapping water yields from streamflow and runoff measurements as correlated with precipitation (11). A maximum of 30 inches of water is yielded annually, on the average, from the high mountains of the Rio Grande Basin in Colorado, while less than 0.1 inch of the annual precipitation falling in the Middle Rio Grande Valley reaches the stream channel. An idea of the actual contribution of water production from each vegetation zone in the Upper Rio Grande is given in table 1. The spruce-fir-aspen contributes most of the flow in Colorado and over 30 percent of that in New Mexico. Ponderosa pine in the New Mexico portion of the basin yields the most water -- about 40 percent of the total -- mostly because it occurs over extensive mountain areas. But, considering the entire Upper Rio Grande Basin, 87 percent of the total water yield comes from the spruce-fir-aspen, ponderosa pine, and mountain grassland which represents only 28 percent of the land area.

PRECIPITATION-RUNOFF RELATION

To understand this divergent runoff contribution, one must be cognizant of the differences in the precipitation pattern and hydrology of small and large watersheds from the highest mountains to the lowlands. In New Mexico, precipitation occurs principally during two seasons -- one in winter and the other in summer. Winter precipitation is mostly snow at the higher elevations and to the north, whereas summer rainfall is received at high intensities below 8000 feet elevation.

LOWLAND SEMI-ARID AND ARID REGION

The monthly precipitation-runoff distribution for a lowland semi-arid grassland watershed is shown in figure 2. On this experimental 40 acre basin only one half inch or 5 percent of the 9 inches of average annual precipitation was yielded as runoff. Waterflow was surface runoff -- a result of high intensity storms. There was no runoff between November 1 and May 1. This represents about the maximum runoff that can be expected from similar small lowland watersheds, for this basin has a narrow, barren and rocky channel with low retention capacity. The other 2 contiguous experimental watersheds on Montano Grant contributed only 4 and 2 percent of the annual precipitation as runoff. These latter watersheds are larger and have greater channel storage capacity in the wider main channels which support deep alluvium and heavy shrub growth. An idea of the opportunity for channel storage and losses of water is given in figure 3. Surface runoff per unit-area decreased with increased watershed size. The larger the watershed, the greater the opportunity for water losses, particularly during the warm season when evaporation-transpiration potential is high and rainstorms are localized.

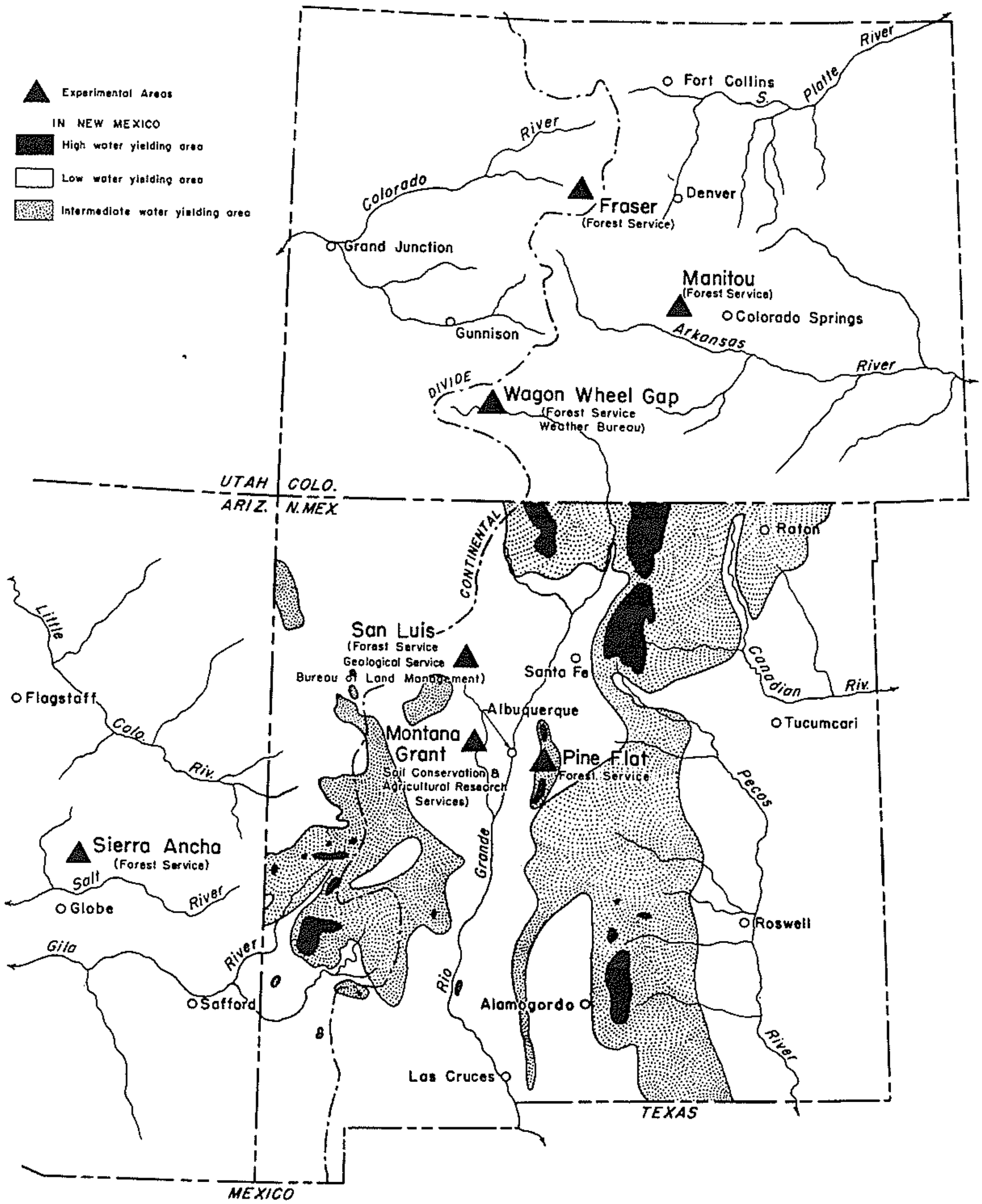

Figure 1.--Experimental areas in and adjacent to New Mexico and water production zones in New Mexico.

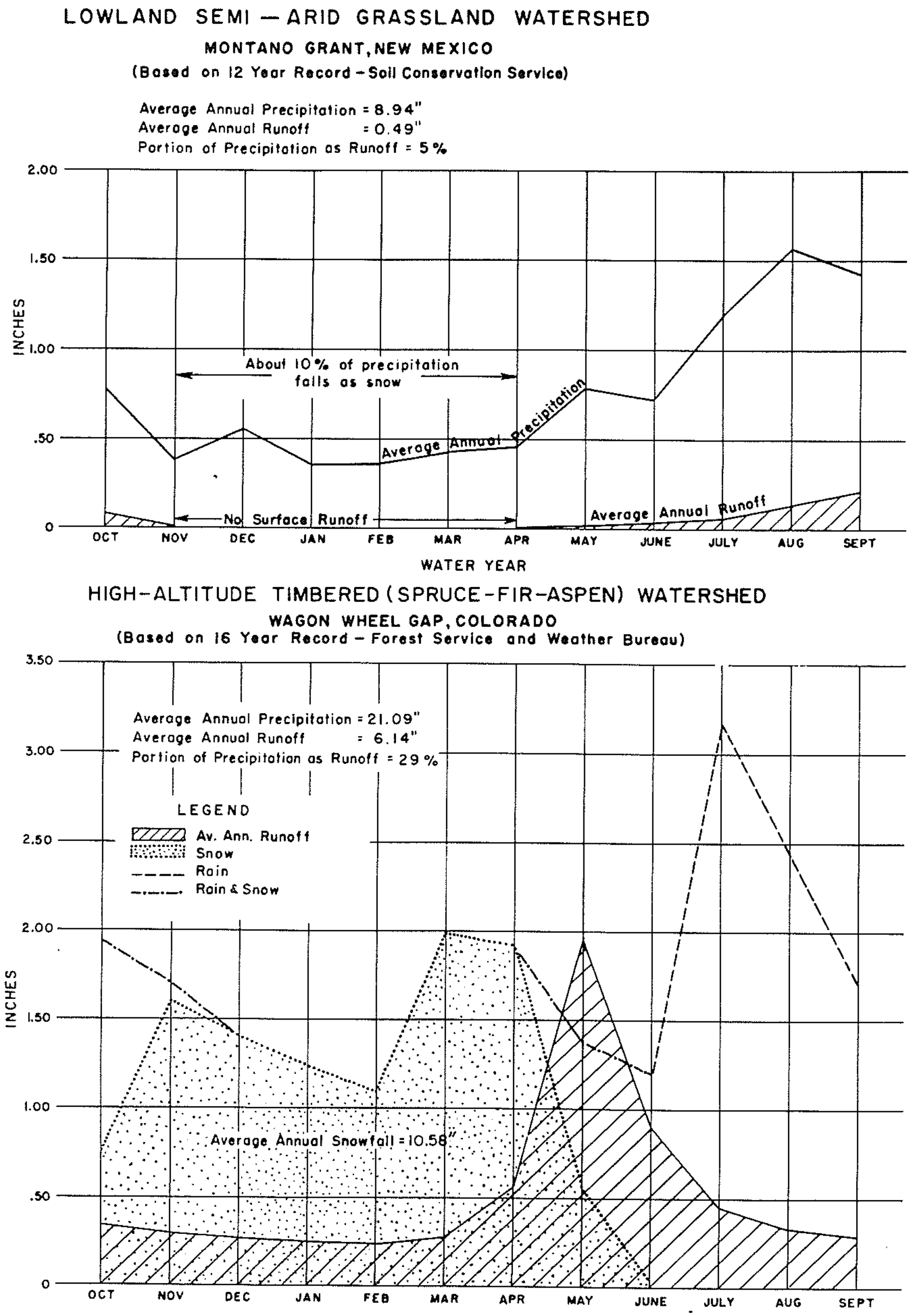

Figure 2.--Monthly precipitation and runoff pattern for a lowland semi-arid grassland watershed and a high-altitude forested watershed.

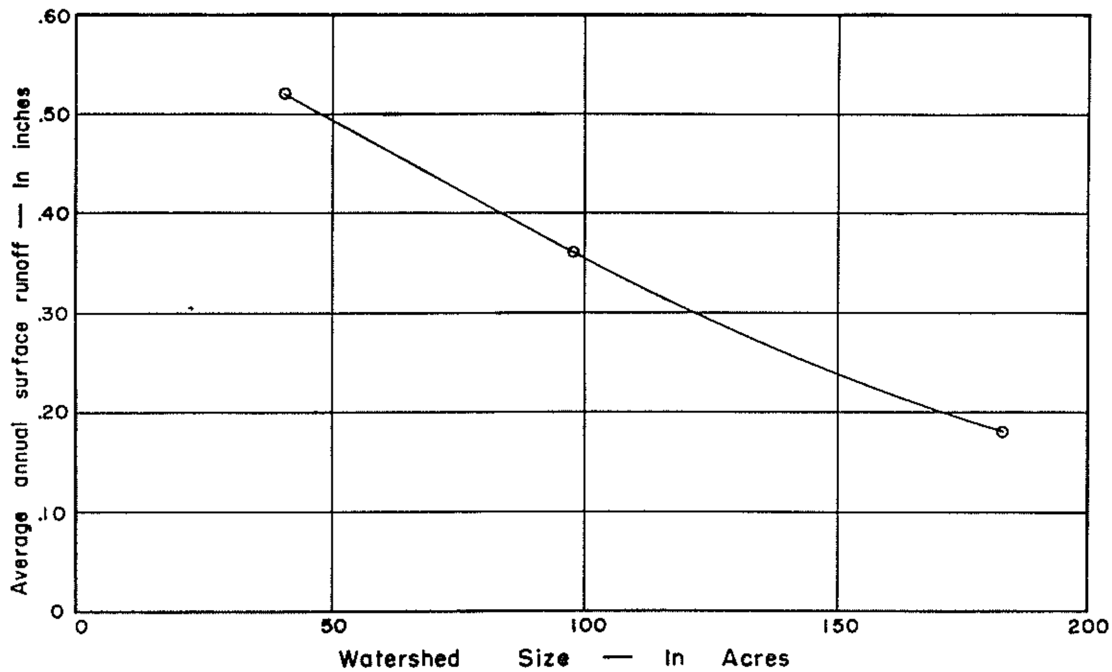

Figure 3.--Relation of runoff to watershed size on Montano Grant in the lowlands.

Table 1.--Sources of water yield to streamflow in the Rio Grande Basin above Elephant Butte Reservoir (11). 1/

Vegetation Zone	Water Yield Contribution	
	Colorado	New Mexico
	Percent	Percent
Spruce-fir-aspen	85.8	31.8
Ponderosa pine	--	40.4
Mountain grassland	11.0	12.1
Pinyon-juniper	2.3	10.8
Sagebrush	0.6	2.4
Semi-arid grassland	0.2	1.4
Greasewood-saltbush	2/	0.6
Cultivated	0.1	0.3
Creosote bush	--	0.1
Dalea brush (Dalea scoparia)	--	0.1

1/ Closed basins excluded.

2/ Less than 0.1 percent.

Thus, we see that water yield from the lowlands is entirely surface runoff contributed from high intensity storms during the high potential evapo-transpiration growing season. As these storms are seldom widespread and mainly localized in character, the rainfall that does not infiltrate the hot, dry slopes is mostly absorbed in the temporary-flow drainage ways connecting the land area with permanent streams. Runoff water leaving localized storm areas must roll down long-dry canyons, washes and gullies and is mostly lost long before reaching the permanent water courses. For example, on the U. S. Geological Survey experimental Cornfield Wash watersheds, runoff averaged 38 acre-feet per square mile during the five year period through 1955. 3/ The average runoff for the Rio Puerco at the downstream Cabezon Station was only 13 acre-feet per square mile for the same five year period. A study of hydrographs of several floods on the reach from Cabezon to Bernardo indicates channel losses may vary from 3 to 8 acre-feet per mile of channel. The lack of permanent streams makes local surface runoff from summer storms an ineffective source of streamflow over most of New Mexico. Yet, surface runoff may attain considerable volume on storm areas and cause much damage through flash floods, erosion and sediment.

MOUNTAINOUS REGION

The precipitation-runoff pattern of the mountains is in sharp contrast to that of the lowlands. Here, a large portion of the precipitation is received when low temperatures prevail. Much of the winter precipitation falls as snow and is slowly released to streamflow during the following spring. An illustration is given in figure 2 for the Wagon Wheel Gap experimental uncut watershed "A". Annual runoff was almost 30 percent of annual precipitation. Though Wagon Wheel Gap is in a rain shadow and does not represent the highest precipitation zone, it does illustrate a region of low evaporation-transpiration potential.

Peak streamflow occurred in May, a result of snowmelting, and continued at a decreasing rate until February, with the exception of a slight increase in October brought about by the cool weather and a drastic reduction in evapo-transpiration. It will be noted that the high summer rainfall had no apparent influence on streamflow which decreased gradually throughout the summer. Surface runoff from land slopes was not noted during the 15 years of study. This is further substantiated in figure 4 which fails to show a relation between summer rainfall and summer runoff, or even fall and winter runoff. Thus, summer rainfall

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3/ Kennon, F. W. and Peterson, H. V.
1956. Runoff and sediment yield in Cornfield Wash, Sandoval County, New Mexico, 37 pp., illus. Typewritten. [Proposed as a water supply paper].

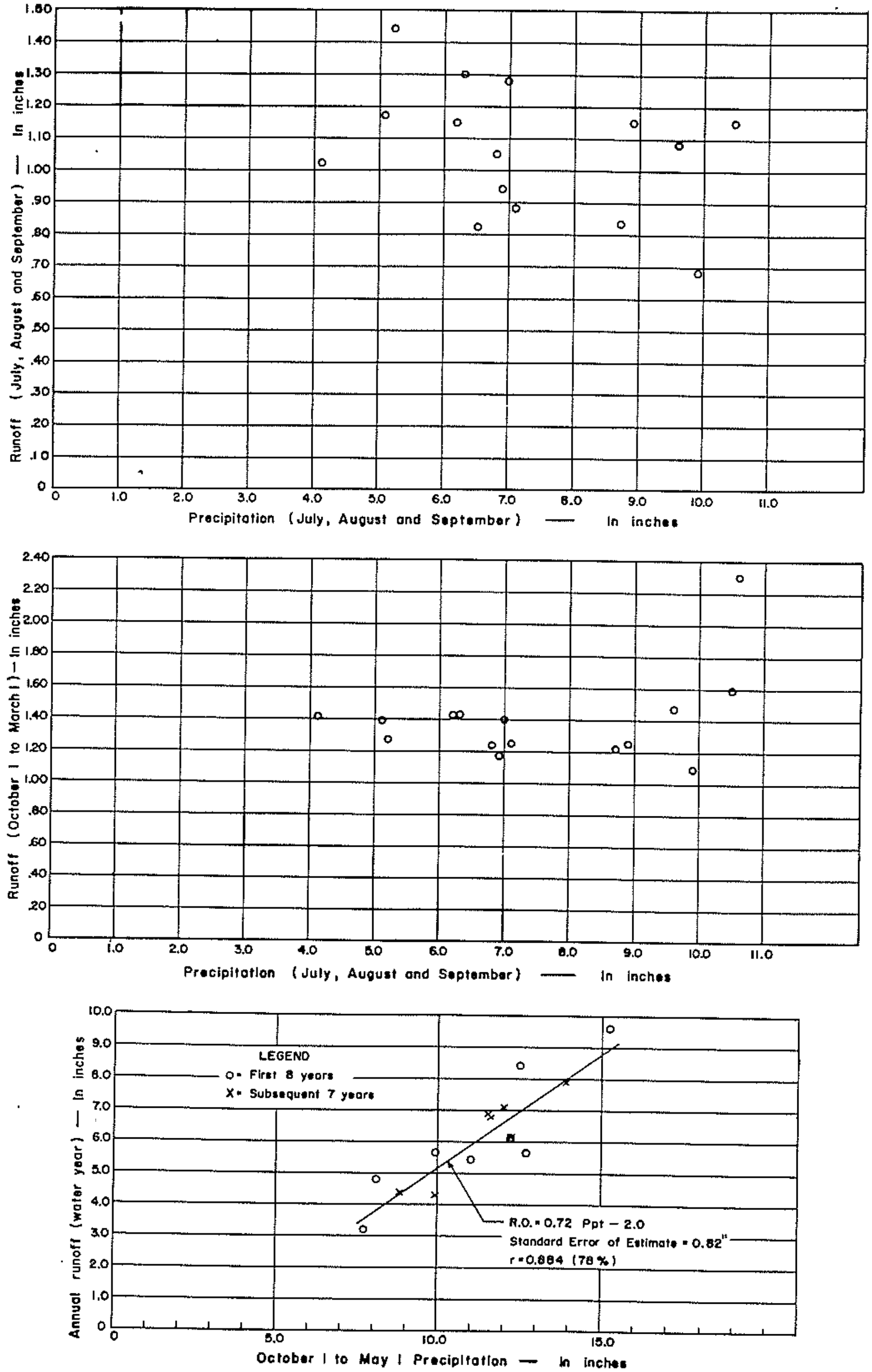

Figure 4.--Relation of runoff to precipitation. Uncut watershed "A", Wagon Wheel Gap, Colorado.

did not flow overland nor did it percolate through the soil. The strong relation between mean seasonal (October 1 to May 1) precipitation and annual runoff shown in figure 4 is in sharp contrast. Over-winter precipitation accounted for 78 percent of the variation in annual runoff. Apparently, melting snow infiltrated into and percolated through the soil before appearing as runoff in the stream channel, accounting for the lag in flow.

The reason for the high correlation between mean seasonal precipitation and annual runoff is that year after year the soil mantle dried out to about wilting point during the growing season. With the advent of cool weather in October, a lowered evapo-transpiration potential, dropping of leaves and curtailment of growth, the first precipitation was used in recharging the soil mantle. Subsequent precipitation and snow melting contributed directly to streamflow as percolation water. The need for satisfying the soil's capillary capacity for water before any appreciable snowmelt water is available to streams has been shown in Utah (7, 10). The amount of water required for soil recharge depends upon the quantity of water remaining in the soil at the end of the dry season. Apparently, summer rains failed to wet the soil completely and most of the soil water added by them was consumed by evapo-transpiration within a relatively short time. The principal effect of summer storms was to provide additional water for the use of plants and for evaporation within the watershed.

A reasonably similar hydrology has been observed on Parker Creek, an experimental watershed, in the Sierra Ancha study area (14). On this 700 acre watershed, slopes are steep and soils shallow so that percolation water drains out rapidly. Surface runoff is negligible from both ponderosa pine on north-facing slopes and mixed grass-chaparral on south-facing slopes. The average annual precipitation of 27 to 28 inches is related to annual runoff but winter precipitation, mostly rain, contributes most of the streamflow. Rainfall from October 1 through May averages about two-thirds of the precipitation, yet contributes 92 percent of the total streamflow. In contrast, only 8 percent of the annual streamflow comes from summer rainfall and more than 80 percent of this streamflow was a result of two large-size winter type storms. These rains occurred in mid-September 1946 and late August 1951 and were sufficient in quantity to satisfy soil moisture deficit.

Even with these 2 storms, summer runoff amounted to only 5.5 percent of summer rainfall while winter runoff averaged 34 percent of winter precipitation. A much higher water yield is obtained at Wagon Wheel Gap where about half of the seasonal (October 1 to May 1) precipitation is soil water runoff.

An attempt has been made to present a picture of the widely divergent water yield hydrology for 2 distinctly different watershed conditions. Yet, this by no means represents the extremes, for many small watersheds produce much less water than the experimental basins on Montano Grant, while on the other hand, small high-altitude watersheds in the Sangre de Cristo range and the southern extension of the San Juan mountains produce considerably more water than those at Wagon Wheel Gap.

Between these extremes lie many conditions depending on elevation, latitude, and position in regard to direction of moist air masses. Water yield from pinyon-juniper lands, though higher than from semi-arid grasslands, is still relatively low. Most of the water production is surface runoff from summer storms, although during wet years, percolation from winter precipitation contributes some water from the higher elevation watersheds and from those with shallow soils. But an important consideration is that during the dormant season, runoff originating almost anywhere on a drainage has a much better chance of reaching perennial streams.

Water production from the ponderosa pine zone is mostly soil water though some surface runoff is contributed from grassland openings and parks in deteriorated condition or where surface soil has been compacted by livestock trampling. The vegetation-soil erosion balance is much more delicate and the erosion hazard is much higher in ponderosa pine than in vegetation zones at higher elevation.

Thus far, our discussion has covered water production zones and how this water is delivered to the main streams. But, how can land managers successfully handle vegetation and soil for maximum production of usable water? The answer to this lies in two basic attributes of vegetation to water. First, a dense cover of trees, grass or even brush is effective in retarding surface runoff and holding soil in place. Secondly, vegetation consumes water through transpiration, interception and evaporation. Obviously, these basic relationships must be balanced properly if vegetation is to serve its highest purpose in controlling surface runoff and erosion and still produce optimum water yields. The main task is then to reduce erosion to safe limits and at the same time reduce water consumption to a practical minimum 4/. How can this be accomplished? It may be fallacious to expect to attain these objectives on each acre of land. We should be able to classify watershed lands according to water or sediment production. In general, lower-lying arid and semi-arid lands are high sediment and low water production areas in contrast to the low sediment and high water production mountainous region. This broad classification gives us a basis on which to operate. Soil stabilization through reduction in surface runoff may need to be practiced on these lowlands, even at the expense of some possible losses in net water production, while clear water may need to be "squeezed out" of the mountain watersheds.

PROBLEMS IN WATER-YIELD CONTROL

Problems of water-yield control vary from place to place, dependent on the attitudes of the water users as well as on the condition of the watersheds. The upstream user -- the one using the water-yielding lands -- whether concerned with growing farm, forage or tree crops, has a considerably different attitude than that of the downstream user. The upstream dryland grower is concerned with controlling water reaching the land so that it will do the least damage and also provide the greatest benefit to his crop. Water flowing off the soil surface is lost in regard to plant growth and presents the threat of erosion. Therefore, in attempting to produce the maximum quantity of plant material, the grower may actually reduce the amount of water yielded from the land, for surface runoff may be induced to enter the soil. But, reducing surface runoff will also reduce erosion and sediment and this improvement may outweigh the reduction in water yield.

On the other hand, the attitude of people downstream from the water-yielding lands is quite different. They are consumers of water coming from the upper watersheds and in the case of floods, the sufferers. Loss according to the down-stream

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4/ Assuming water production is in greater demand and of higher value than forage, wood, wildlife, and recreation.

attitude includes loss in opportunity of use by damaging floods or high flows occurring when waterflow cannot be utilized, loss in quality by sediment and salts and loss in quantity of flow caused by evapo-transpiration.

FLOODS

Floods in New Mexico are of two general types; spring floods resulting primarily from melting snow or rain falling on snow, and flash floods from high intensity summer rainstorms. In the Upper Rio Grande, future annual flood damages from spring flows is estimated at about 1 million dollars (11). Most everyone is familiar with the extensive damages resulting from flash floods in recent years. Some of the communities that have suffered considerable damage are Albuquerque, Bernalillo, Roswell, Artesia, Carlsbad, Las Cruces, Hondo and Pojoaque. Flash floods have also caused considerable damage to farmlands and other improvements. These damages have occurred during a prolonged period of drought when annual precipitation was much less than the long-time average.

SEDIMENT

Associated with flash floods is the problem of sediment transportation and deposition. Sediment damage in the Upper Rio Grande Basin is estimated at 2 million dollars annually (11) caused by depletion of reservoir capacities, aggradation of river channels, detrimental deposition on lands and crops and increased maintenance of irrigation facilities. The water wasted by non-beneficial vegetation (phreatophytes) occupying sediment deposits and the contamination of clear mountain water in transit to lower-lying, water-use areas are additional damages not included in the above estimate.

WATER QUALITY

The increase in salt content in going down the Rio Grande is associated with the increase in sediment. Annual crop losses due to salinity are considerable in the Rio Grande.

PHREATOPHYTES

Losses of water by phreatophytic vegetation (plants tapping the water table or capillary fringe) were estimated at about 240,000 acre-feet annually in the Upper Rio Grande before the rehabilitation project was started by the Bureau of Reclamation in recent years. Lowry (27) presented evidence that channel rectification, reservoir storage, drainage of bottomlands and by-passing water around phreatophyte areas appreciably reduced evaporation waste in the Rio Grande. The quantity of water saved by removing phreatophytes is still questionable and must await later evaluation. Poisoning plants or clearing land is only a temporary measure, as eventually, regrowth or other vegetation will occupy the site.

RESEARCH FINDINGS

GRAZING LANDS

Most of the problems dealing with the control of water yield (floods, sediment, salinity and wasteful evapo-transpiration) originate on lands lying below 8000 feet elevation. As these lands are used primarily for grazing, a review of investigations and research results covering the influence of grazing on water run-off and erosion appears necessary.

The effect of heavy grazing upon both plant cover and erosion has been clearly shown by the historical study and field survey reported in 1937 by Cooperrider and Hendricks (5) and by subsequent Soil Conservation Service studies in the Rio Grande Basin (37, 39). According to these studies, range deterioration resulted in increased surface runoff and erosion. Plot studies in Colorado, Arizona, Utah and elsewhere in the west, have shown that heavily grazed as well as deteriorated rangelands contribute considerably more surface runoff and erosion than protected or lightly grazed ranges or those in good condition (4, 6, 12, 31, 36, 43). Heavy grazing results in a reduction in the infiltration capacity of the soil by reducing the amount of vegetation and litter covering the ground as well as by compacting surface soil through trampling 5/ (32). Too heavy grazing also reduces the vigor of perennial grasses and eventually allows the site to be occupied by less desirable annuals, half shrubs and woody plants (38). These plants are a poor substitute for a good cover of perennial grasses in regard to infiltration and erosion.

Composition and density of herbaceous cover can be improved by control of grazing animals and by mechanical means. Improvement through animal control can be attained in a reasonable time in the moist mountain grassland zone. But in the semi-arid and arid zones, recovery of vegetation vigor, density and composition is extremely slow. For example, in the semi-desert portion of the Salt River watershed, exclusion of livestock for about 20 years resulted in a very small increase in grass density and no curtailment of erosion (38). The same has been observed by other investigators (15, 16, 30) studying vegetation in New Mexico. Research

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5/ Dortignac, E. J. and Love, L. D.
1957. Infiltration as affected by vegetation, soil and cattle grazing in Colorado ponderosa pine ranges. 122 pp., illus. Typewritten. [Proposed as a U. S. Dept. of Agr. Tech. Bull.].

has not shown how to satisfactorily rehabilitate deteriorated ranges with less than 14 inches annual precipitation under continued livestock use, particularly during drought years. Most reseeding efforts on these dry ranges have thus far been failures.

A start has been made in Idaho and Utah toward evaluating the density of range cover needed to reduce surface runoff and erosion to safe limits (28, 31). These studies have been made in the moist zones and it appears that at least 65 to 70 percent of the soil should be covered with vegetation and litter. Maintenance of this quantity of cover may be impossible in the arid and semi-arid zones.

An idea of how grazing may influence the yield of water was reported by Martin and Rich (29) utilizing a lysimeter study in grassland on the Sierra Ancha Experimental Forest. Three lysimeters of undisturbed soil underlain with impervious quartzite bedrock were used in this study. At the time of installation, plant cover was sparse, a result of previous heavy grazing. Grass seeding, fertilizing and watering were used to increase cover density. Then, under no other treatment, surface flow and drainage were measured for seven years and no significant differences were observed. Starting in 1942, one lysimeter was grazed heavily each year by sheep, one left untouched and one grazed moderately. Recognizing that these treatments which involved grazing by two mature ewes for 4 days, annually, is not comparable to grazing by a large number of sheep on rangeland, yet, the results are noteworthy. Ground-cover density decreased on both grazed lysimeters, the decrease being greater on the heavily grazed plot. Surface runoff was small during the low intensity, long-duration winter storms and percolation or drainage through them was about the same regardless of treatment. During the high-intensity summer rainstorms, the quantity of surface runoff and erosion increased with increased intensity of grazing. Yet, total water yield (surface plus subsurface runoff) was the same from all three plant-soil conditions, amounting to about one-third of the precipitation. Grazing use greatly influenced the proportion of surface runoff to percolation flow, but total quantity of yield remained about the same. Since the entire watershed was wetted by this general-type storm during a period of low evapo-transpiration potential, it is probable that most runoff reached the perennial stream channels.

Another lysimeter study at Sierra Ancha has shown there is a considerable difference between the times of year when different kinds of vegetation draw heavily on soil moisture (33). In comparing grass-cover with shrub-cover and bare soil it was found that during the summer there was no significant difference in evaporative losses. Nearly all of the water added by summer rains was lost so that no water was yielded as drainage. Important differences in evapo-transpiration were found during the winter and spring when appreciable quantities of water drained out of the lysimeters. During this period, grass cover lost between 70 and 81 percent, shrubs between 74 and 86 percent and bare soil between 52 and 72 percent of the precipitation. Ruling out the bare soil as undesirable from the standpoint of erosion, these results suggest that water yield might be increased in this area if lightly grazed grass replaced a cover of shrubs.

FORESTED LANDS

Since the mountain lands contribute an extremely large portion of the water yield in New Mexico, it follows that these lands should be managed, if possible, to contribute optimum yields of usable water. The most promising method for increasing water yields without damaging the watersheds appears to be that of improved management of the mountain snowpack. Snow accumulation and the time and amount of water yield from snowmelt are definitely subject to control by harvesting the tree crop. High altitude alpine areas offer some opportunity for management but in view of the extensiveness of the forested region in New Mexico, intensive but careful forest-watershed management in this zone appears most fruitful.

Snow Water

Many studies covering conditions in Colorado, Arizona, California and Idaho have shown that forests favor the evaporation of snow, primarily through their ability to intercept a portion of the snowfall and expose it to higher rates of evaporation than in the snowpack. All of these studies have indicated an inverse relation between tree density and snow accumulation. Cutting trees reduced interception losses approximately in proportion to the reduction in crown cover.

At Fraser, removal of all sawlogs from a mature lodgepole pine stand increased the water equivalent of the snowpack by about 30 percent (42), while clear cutting alternate narrow strips in an old and dense spruce forest resulted in a somewhat lower increase. Thinning young lodgepole pine stands increased the water equivalent of snow accumulation by 23 percent when 85 percent of original trees were cut and 17 percent when only half of the trees were cut (17). Similar results differing only in quantities were obtained in Arizona, California and Idaho (4, 20, 23). Generally, these investigations have indicated the greatest accumulation of snow in small openings in the forest and the least under dense forest canopy while tree stands opened up by logging had snowpacks of intermediate water content.

These studies have been empirical and provided results for certain conditions and localities. We need to know much more about the influence of topography and trees on microclimate and about wind, vapor pressure and temperature differences on various slope exposures, stand densities and variable-sized openings. The effect of heat radiation to the snowpack (by trees to the north of openings) on accumulation and melting is not known. Likewise, little information is available on reduction in evapoation from snow by retardation of air movement near the snow surface; on the effect of interception of diffuse sky radiation by trees; and on the relation of the snow crust and other surface conditions on the reflection of sunlight. Studies concerned with the relation of tree-cover to the physics of snowpack accumulation are needed before widespread forest-watershed management can be effectively practiced.

The effect of trees on trapping drifting snow from bare ridge tops and other exposed locations should be evaluated. The practicability of piling snow into deep drifts in the shade of trees, on north slopes and in shaded ravines as a means of reducing evaporation losses and delaying melt to prolong streamflow should be determined. Snow accumulation is usually greater on north aspects and least on slopes facing south. Aspect has been found to affect spring snowmelt in a similar manner (7, 41).

On the basis of present knowledge, logging high altitude timber such as spruce-fir in an alternate pattern of clear cut strips about equal to the height of trees seems desirable from the viewpoint of water yield. But how should strips be oriented? Should maximum protection from wind or solar radiation be the objective or should strips be on a contour? Studies in the central Sierra-Nevada mountains in California showed that evaporation losses from the snowpack, under eleven conditions of cover were small -- averaging less than 1.5 inches from December 1 to June 1 and less than 0.5 inch in any one month (23). Cutover mixed conifer, open logged and open meadow had the highest evaporation losses while mature red fir, mature ponderosa pine and a large opening near the river had the lowest evaporation losses. Yet, when comparing evaporation from snow under crowns with small openings between crowns, 5 out of 7 forested conditions had less evaporation from the snowpack in the small openings.

The rate of snowmelting as affected by cutting of trees is important in regard to spring flood flows and maintaining perennial flow during the late season. Maintenance of a dense forest cover tends to delay the rate of snow melting and reduce the contribution to flood flows, particularly, when rain occurs. According to Kittredge (23), the daily rate of melting might be as much as 0.1 inch of water lower in forested than in open areas. He found that snowmelt in a white fir stand was about half that in a large clearing and this quantity compared favorably with Anderson's recent analysis (1). According to Goodell (17), thinning dense young lodgepole pine stands accelerated snowmelt, amounting to more than 2 inches additional melt during the first 3 weeks of the melting period.

To retard melting of snow and prolong its contribution to streamflow later into the summer involves both the amount of snow in storage and its rate of release by melting. In creating small openings less than twice the height of trees in width by clear-cutting, where ecologically and silviculturally feasible, one might expect the most water under prolonged flow. Strip cutting might give almost as good results providing clear cut zones are narrow -- about half the height of the trees. The proportion of the total area to be clear cut in small groups or narrow strips should be based on the need for providing belts of uncut timber for wind protection and shading. Anderson (1) recently suggested that maximum accumulation of the snowpack might be obtained by cutting the forest so as to retain the most shade but at the same time reducing the height of trees to the north. His analysis indicated that shade from trees to the south was twice as effective in increasing snow accumulation by April 1 as radiation from trees to the north was in reducing the snowpack. He proposed harvesting trees in successive narrow strips at right angles to maximum solar radiation to produce a "wall-and step" pattern with the wall to the south.

Although a considerable number of plot studies have been made on the effect of vegetation on snow accumulation and melting, this type of information is not available on a watershed basis.

Water Yield as Affected by Vegetation Changes

Love's (24) recent analysis indicates a reduction in evapotranspiration and interception by beetle-killed spruce and pine was associated with increased streamflow in the 206 square mile White River drainage in Colorado. Preliminary data on the effect of timber cutting on streamflow should be forthcoming in the near future from Fool Creek in the Fraser Experimental Forest and from Workman Creek at Sierra Ancha. Until then, we must draw upon the results of cutting and tree removal from the Wagon Wheel Gap watersheds.

Results of this study are adequately shown in figure 5, which relates annual runoff of watershed "A", the control to the treated watershed "B", both before and after tree cutting. In the 8 years prior to tree cutting, a highly significant straight-line relationship was found. The straight-line fit by the method of least squares accounts for 98 percent of the variation. Under such conditions, there is no need to introduce the factor of precipitation, which was very similar on the 2 watersheds. The points for years subsequent to deforestation show that the full effect of treatment was not felt until the third year after tree cutting and removal and there was a gradual decrease to the seventh year. The increased runoff by years is given in table 3. The average annual increase in streamflow amounted to about 0.94 inch or 15 percent. Bates and Henry (2), the original authors, and Hoyt and Troxell (19) in 1932, using an entirely different approach obtained almost the same result; that is, 0.96 inch. Hoyt and Troxell, by correlating daily discharges, showed the same relative yearly increases but by the seventh year the increase had dwindled to .04 percent.

A partial explanation for the delay in maximum increase in streamflow occurring in the third year may be gained by review of the treatment procedure. Although most of Watershed B was cut over during the summer of 1919, a strip was purposely left along the stream channel until 1920. Slash from the larger conifers and entire stems and tops of smaller evergreens and aspens were piled in windrows and not burned until September 1920, just prior to the start of the second year of treatment. Plot studies in Colorado have shown that dense young lodgepole pine trees felled in thinning operations were as effective in intercepting rainfall as when standing, as long as they held their needles (17). Snow accumulation would be expected to be influenced in a similar manner.

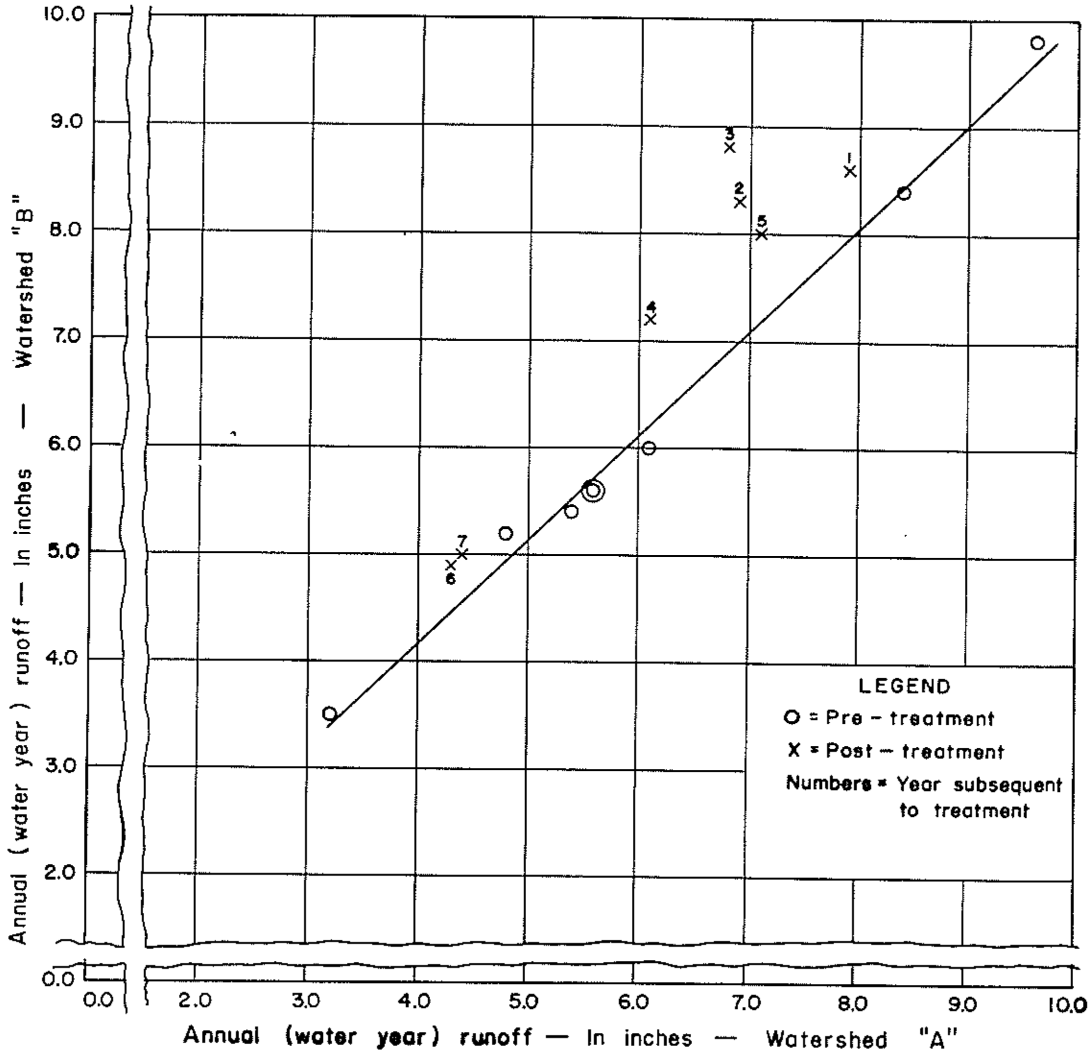

Figure 5.--Relation of annual (water year) runoff of "A" (uncut) to "B" (cut) watershed, Wagon Wheel Gap, Colorado.

Table 3.--Increased runoff of watershed "B" after tree cutting and removal. Wagon Wheel Gap, Colorado.

Time subsequent to treatment	Increased runoff of "B" (from regression line)	
Year	Inches	Percent
1	0.65	8.2
2	1.30	18.6
3	1.95	28.3
4	1.00	16.1
5	0.82	11.4
6	0.45	9.9
7	0.42	9.4
Average	0.94	14.9

The increase in spring flood runoff after deforestation was much greater than during the balance of the year. According to the analysis by Bates and Henry the annual increase in flow was distributed as follows:

	Increase in flow	
	Inches	Percent
Before flood crest	0.68	71
Decline of flood	0.12	12.5
Summer months	0.09	9.5
Winter months	0.07	7
Annual	0.96	100.0

In other words, 83.5 percent of the increase occurred during the flood or high flow period and only 10 percent during the summer months. The evaluation by Hoyt and Troxell did not differ greatly, for example, they concluded that the increase in summer runoff amounted to a little less than 0.15 inch for a 12 percent summer flow increase or about 15 percent of the annual increase.

There is no certainty as to the exact causes of these increases in runoff. Bates and Henry deduced that most of the increase was caused by a reduction in tree interception losses of snow and that decreased evapo-transpiration during the summer was much less important. In view of the relation previously shown between over-winter precipitation and annual streamflow, these conclusions appear sound for this study.

Other important results of deforestation were that flood crests were advanced three days -- a result of earlier melting and erosion increased 5 to 15 fold but averaged only 17 pounds per acre -- an unimportant soil loss.

One of the reasons for such small soil losses is that cutting and removal of woody vegetation was carefully done avoiding exposure of bare soil. Another is that soils were very porous.

The vegetation cover on watershed B prior to treatment was as follows:

Type of cover	Area percentage
Aspen without conifers	43.8
Aspen with conifers	17.1
Conifers	23.4
Barren, grass and burned-over spruce	15.7

A greater proportion of watershed A was in conifers than on watershed B prior to treatment. A field examination of these watersheds in the summer of 1953 indicated that little change in composition of vegetation cover occurred in the intervening period on the uncut watershed. Watershed B supported a thick stand of aspen which apparently is denser than the original stand. Since the period of evaluation showed the maximum streamflow increase during the third year and a steady decline thereafter, one may wonder whether less water is now produced on B than before treatment. Only a small amount of information on the relative merits of aspen versus conifers in regard to water yield is available. Plot studies in Colorado indicated that aspen and open grassland intercepted smaller amounts of precipitation than a dense stand of young lodgepole pine (13). In this study, winter snow storage plus net precipitation reaching the ground during snowmelting was highest under aspen:

	Net precipitation Inches
Aspen	14.8
Grass (open fields)	13.3
Lodgepole pine	11.6

But, on the other hand, aspen, a broad-leaved and deep-rooted tree, would be expected to use greater quantities of soil moisture during the active growing season (May to October) than spruce or fir.

Results obtained on a study plot in northern Utah indicate the possibility of reducing evaporative soil moisture losses by altering vegetation (9). No surface runoff nor erosion occurred on three plots in an aspen grove during a fifteen year period. Grazing was excluded. In 1947, all aspen trees were removed from one plot, all vegetation removed from another, and the third left untreated. In regard to summer evaporative losses of soil moisture, Croft found that by the end of the season field capacity deficits were:

Bare soil	--	3 inches
Herbaceous (trees removed)	--	8 inches
Aspen	--	11 inches

Removal of aspen brought about a saving of 3 inches of water and removal of all vegetation, 8 inches. But removal of all vegetation unleashed erosion at the rate of 10 tons per acre during 3 summers of rain, less intense than prior to treatment.

Another factor which may have affected water yields at Wagon Wheel Gap is that of evapo-transpiration by riparian vegetation.

RIPARIAN VEGETATION

Only a limited amount of research data is now available on evapo-transpiration along stream channels in the mountains of the west. Two studies, one in Utah and one in southern California, provide some preliminary leads. Croft (8) estimated from analysis of diurnal and seasonal fluctuations of Farmington Creek in the Wasatch mountains in Utah that riparian water losses equalled one-third of the total streamflow between August and October. The canyon bottom vegetation consisted of willow, alder, cottonwood, mixed shrub, a few fir and herbaceous vegetation including grasses. Young and Blaney (44) used 3 stream gaging stations along 8000 feet of channel in Cold Water Canyon in the southern California mountains to evaluate riparian losses. Calculations indicated that over the riparian zone about 45 feet wide that channel losses varied from an average of about 6 to 11.5 inches during the summer months.

But this information is too meager to apply directly to New Mexico conditions. Apparently, removal of certain tree species, mainly broad leaves, along stream courses may appreciably reduce water losses but when this saving is spread over an entire watershed the increase may be relatively small. Other considerations from the water yield standpoint need to be mentioned here. If trees were removed along certain perennial stream courses then some other type of low-water using vegetation such as grass would need to replace them. Often stream margins are more severely damaged by livestock and big-game trampling than land more distant from the water courses. Damage is partly due to the heavy trampling but mostly because soils are trampled when wet. As a consequence, streambanks are often beaten down and eroded during high waterflow stages. Such damage can be observed on the high-altitude grassy meadows in New Mexico where livestock and big game concentrate. Another factor which needs study and evaluation is the influence of trees in overcoming the compacting effects exerted on soil by trampling animals. The only information available on this subject is the Emmenthal study in Switzerland which indicated trees in pastures were beneficial in maintaining porous soils (3).

ALTERNATIVE TYPES OF VEGETATION

Although vegetation type conversion may have considerable appeal to the layman it is covered last because present opportunity for successful application appears limited. Moreover, little information is available on how to change and maintain a particular vegetation type without damaging the watershed. Research at hand, based solely on small plot studies indicates herbaceous cover may use less water than woody plants. Likewise, certain annuals, with limited root systems may use less water than perennial grasses with more extensive root systems for a comparable growth period. But, water use by plants varies considerably according to species, time of year and available soil water. For example, crested wheatgrass grows most actively during the cool spring period in contrast to blue grama, a summer grower. At Sierra Ancha (38) it was found that perennial grasses (summer growers) used less water during the water-yielding period (October 1 to June 1) than a deteriorated watershed cover consisting of winter annuals mostly filaree, snakeweed and evergreen shrubs. Thus, from the standpoint of water yield alone, under similar situations, a perennial grass cover might be the goal. Likewise, in New Mexico, from the standpoint of water yield, one might favor reseeding deteriorated high-elevation mountain meadows and parks with summer growing perennial bunchgrasses such as mountain muhly, Arizona and sheep fescue, rather than using cool-season growers such as wheatgrasses.

The opportunity for alternative kinds of vegetation is much greater in the more humid east than in New Mexico where precipitation is deficient. In the moist region at the higher elevations in New Mexico, the cool temperatures and the short growing season limit the type of vegetation that can be grown. In general, the greatest opportunity for change in cover type is along the fringe or transition zones but the areal extent is limited. However, some conversion of vegetation types has occurred in New Mexico. These are:

1. Grassland, woodland and sagebrush to cropland and vice versa.
2. Grassland to sagebrush -- probably through over-use by animals -- sagebrush to grassland through reseeding.
3. Encroachment of juniper and pinyon into grassland -- possibly a result of over-use. Re-trenchment of juniper and pinyon -- a result of drought. Removal of juniper and pinyon by mechanical methods.
4. Conversion of ponderosa pine timberlands to mountain brush -- a result of fire.
5. Conversion of spruce-fir to aspen -- a result of fire.

Research conducted almost entirely in the eastern United States mostly from plots or small watersheds has always shown higher surface runoff and erosion from row and field crops when compared with other vegetation (4). This is in line with logical deduction since dry-farming leaves the soil bare part of the year and in the case of row crops, partly bare in all seasons.

Regardless of how appealing type conversion may appear, its potential may be restricted when we consider management strictly from the water yield standpoint. For example, in north-central New Mexico, not more than 150,000 acres of sagebrush-woodland can be reseeded successfully to grass under the present status of knowledge. The cost of this operation has averaged about $8 per acre. Likewise, removal of juniper and subsequent maintenance is a costly operation and may not be economically justified from the standpoint of range improvement alone. The question might be raised as to possible changes in water or sediment yield from these range improvement operations. Some preliminary information derived from small infiltrometer plot (2.5 square feet) tests in north-central New Mexico indicates reseeding, as now practiced, has only a temporary effect on infiltration and erosion and that subsequent grazing use is the dominant factor determining surface runoff and sediment contributed from these areas.

An indication of the effect of removal of pinyon trees on water yield may be gleaned from results of the soil moisture study at Pine Flat, located in the upper elevation pinyon-juniper zone. The march of soil moisture in the upper 12" of soil under 3 cover conditions; pinyon trees, herbaceous cover (mostly blue grama) and bare soil, is shown in fig. 6. June, July and August were the rainy months, yet, summer rains were insufficient to restore soil moisture which was entirely depleted by fall. But the lower evapo-transpiration rate in late fall and early winter allowed precipitation to replenish soil moisture depletion. Based on this first year's measurements, soil moisture penetration was greater during the over-winter period of snowfall and low temperatures than during the growing season. Moisture failed to penetrate below 12 inches under pinyon or blue grama during the growing season nor below 21 inches during the dormant season. Soil moisture losses in the top 12 inches of soil during depletion periods amounted to 8 inches under herbaceous cover and 7 inches under pinyon trees. As over-winter (November 1 to April 1) precipitation was about 90 percent of the long-term average, based on the Tijeras Ranger Station record, it is unlikely that soil water would percolate to bedrock at 30 inches during years with similar or lower precipitation. Replacement of pinyon trees with herbaceous vegetation cannot be expected to appreciably increase water yields through percolation, except during years with above-average dormant season precipitation.

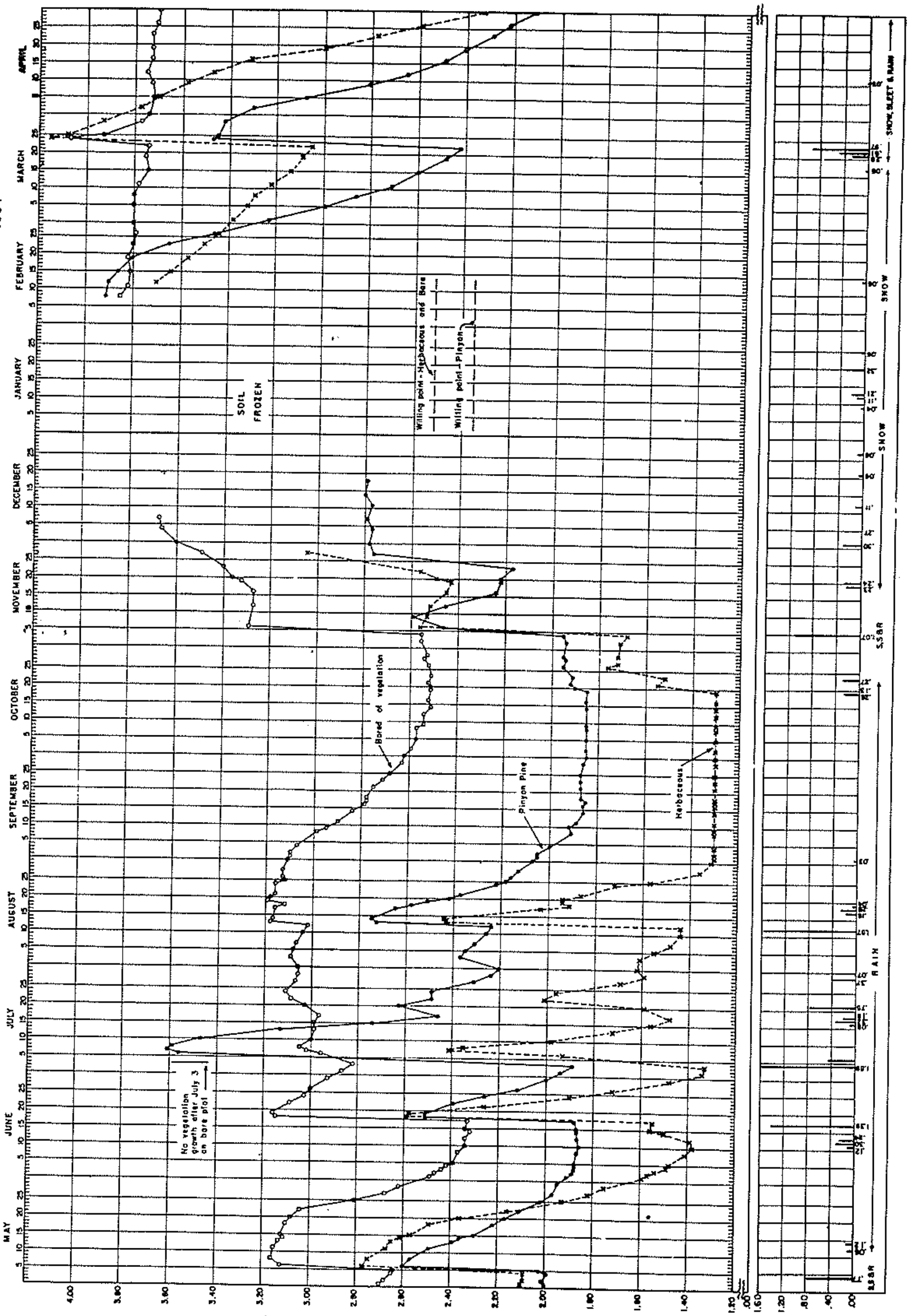

Figure 6.--Moisture content in first 12 inches of surface soil under pinyon pine, blue grama and bare soil. Pine Flat, New Mexico.

The main watershed problem in the pinyon-juniper zone of New Mexico is soil stabilization and this should be done by reducing surface runoff during the summer high intensity rainstorms. In accomplishing this, the amount of water yielded from the land may be actually reduced but by reducing surface runoff and erosion, both the regimen and quality of water will be improved and this kind of improvement seems more important than any reduction in water yield that may accompany it.

Above 8000 to 8500 feet, as mentioned previously, annual precipitation exceeds evapo-transpiration losses. Snow is the dominant form of precipitation and the snow cover persists to early summer with remnants still present in July in the alpine region of the Sangre de Cristo range. Management of forests through good sound practices appears to offer the most promising method of maintaining or possibly increasing water yields.

Fire as a Tool

Controlled burning is, at present, a subject of considerable controversy in the southwest. Much of it stems from the inadequacy of research information. Another is the difference in points of view of individuals which ties back to differences in wildland management objectives. Controlled burning has been advocated to thin pine reproduction and even for attempting type conversion. Burning as a means of changing vegetation can have temporary or lasting effects depending on the kind of vegetation burned, the degree to which it is burned, amount and type of vegetation killed by the fire and treatment given the land after the fire.

It is important to recognize that fires in grassland are considerably different than those in forests. Grassland fires usually consume everything above ground as flames are carried by dense dry fuel that forms a more or less continuous cover over the soil. Grass fires move quickly and the soil is heated for brief periods. Hence, seed on the ground and root crowns of perennial grasses are not killed. Rapid recovery of grassland from fire has been observed in the southeast, in the Prairie and in the semi-arid California foothills.

In contrast, forest fires are considerably more variable in the way they burn and in their effects on vegetation. When burning takes place during hot dry weather, all vegetation from the ground to treetops may be burned over large areas. Under less severe weather conditions fire may creep through the litter or consume low-growing vegetation. Between these extremes lie many conditions difficult of appraisal.

Studies in California, Utah, and elsewhere have shown (with one exception) that any type of burning on forest, brushland and woodland-grassland has increased surface runoff and erosion (4, 22, 34, 40). In July 1942, a lightning fire burned 100 acres of ponderosa pine and Douglas Fir within the Sierra Ancha Experimental Forest. Flash runoff and soil losses were measured from subsequent late July rainstorms on this watershed but the adjacent unburned watershed produced no flash flows nor erosion (18).

One need not travel far to see the effects of wildfires on former ponderosa pine timberlands in New Mexico. In many areas, mountain brush, mainly oak or Mexican locust, occupies the land. The Sacramento mountains, particularly the west side and burned over mountain-sides in north central New Mexico, provide good examples of this type of conversion. At higher elevations and on cool north slopes aspen is more apt to invade burned over coniferous forests (21).

CONCLUSION

In conclusion, the maintenance of an adequate supply of usable water for irrigation, domestic use, recreation, industry and power is the principal problem facing arid New Mexico today. How present water supplies can be maintained or improved in quality through management of vegetation and soil is now uppermost in many minds. It is, therefore, timely that problems associated with the use of watersheds be critically examined and that greater effort be made to put present day knowledge to practice. It is also timely that the need for certain types of information be brought to the attention of those concerned. For only through better knowledge of watershed behavior under variable climate, vegetation, soil and use can we expect to understand and solve the problems now confronting us. It is hoped that this presentation will contribute in a small way toward a better understanding of the water problems and the possibilities for improvement.

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