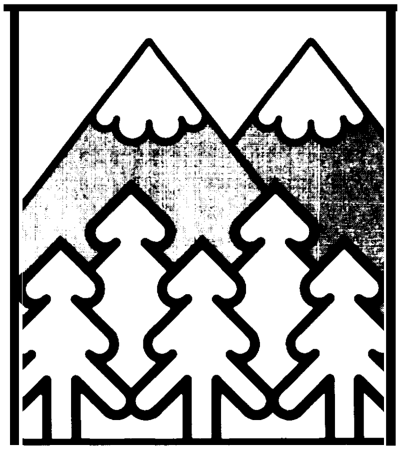

Technologies Affecting Precipitation and Runoff

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Chapter VI

Technologies Affecting Precipitation and Runoff

Most of the water used by agriculture in the Western United States originates as precipitation, then runoff. The hope exists that large amounts of additional water could be made available by altering these processes a small amount. A variety of technologies have been developed either to increase or predict the surface runoff from watersheds of the Western United States. These include augmentation methods such as weather modification ("cloud seeding"), watershed management through vegetation removal or replacement, and streamflow forecasting. Each of these has been supported by Federal research, and interest in each remains high.

This chapter illustrates the interrelated nature of these technologies and assesses the degree to which they increase or manage precipitation and surface runoff for the region's agriculture. The chapter is based on the extensive research literature about the United States and similar hydrologic environments throughout the world. A definitive regionwide assessment of these technologies cannot be made here, Their effects on distant downstream users may be difficult to measure, their results may not be applicable to large geographic areas, and few data syntheses exist. Considerable disagreement persists, then, regarding the potential of these technologies as well as the legal and institutional ramifications of their application.

Box J

> "If we lived in a desert and our lives depended on a water supply that came out of a steel tube, we would inevitably watch that tube and talk about it understandingly. No citizen would need to be lectured about his duty towards its care or spurred to help if it were in danger. Teachers of civics in such a community might develop a sense of public responsibility, not only by describing the remote beginnings of the commonwealth, but also how that tube got built, how long it would last, how vital the intake might be if the rainfall on the forested mountains nearby ever changed in seasonal habit or amount. It would be a most unimaginative person, or a stupid one, who could not see the vital relation between the mountains, the forests, that tube and himself. "

SOURCE: Isaiah Bowman, "Headwaters Control and Use-Influence of Vegetation on Land-Water Relationships," *Proc.* Upstream *Engin. Conf.* Washington, D.C., **pp. 76-95, 1937.**

THE WATER SETTING

In the Western United States, a watershed may be as large as that of the Missouri River basin, with a surface area of at least 500,000 square miles (mi^2), or as small as an ephemeral tributary to that river, with a surface area of only a few tens of acres. Watersheds in the Western United States, at their largest geographic scale, encompass a wide range of climates, geology, soil and vegetation types, and land use practices. Even the smallest watersheds are seldom homogeneous in all of these factors.

Water may leave a watershed in a variety of ways. The most obvious is surface runoff as a river or stream. Water also may leave a watershed by percolating to ground water. The extent to which this occurs is dependent on the ability of the soil and rocks of the basin to transmit water. Over much of the Western United States, the primary means by which water leaves the watershed is by evapotranspiration (ET). ET is generally greatest in the arid and semiarid portions of watersheds and least in high-altitude mountain watersheds. Thus, ET may account for almost all of the precipitation falling on a watershed in an arid portion of the Lower Colorado River Basin, while it may account for only a small fraction of the precipitation falling in an alpine environment at the headwaters of that river.

Each year, an estimated 1.5 billion acre-ft of water are added by precipitation to the water supplies of the Western United States. Of this amount, approximately 500 million to 550 million acre-ft form the surface runoff of the region, 50 million acre-ft enter into the ground water reserves, and the major portion is returned to the atmosphere by evaporation or transpiration from vegetation. The bulk of the surface runoff is derived from the melting mountain snowpack, which produces an estimated 70 percent, or 350 million acre-ft, of the runoff of the region (table 36).

Table 36.—Variable Percentage of Surface Runoff From the Mountain Snowpack

Estimated snowmelt fraction of the total annual surface runoff for those Western States where melting mountain snowpack is the principal source of surface runoff.

State	Snowmelt fraction of total annual streamflow
Arizona	0.74
California	0.73
Colorado	0.73
Idaho	0.67
Montana	0.70
Nevada	0.65
New Mexico	0.71
Oregon	0.67
Utah	0.74
Washington	0.67
Wyoming	0.74
	0.70

SOURCE P **Castruccio, H. Loats,** D. Lloyd, and P Newman, *Application Systems Verificatlon and* Transfer Project, *Volume VII: Cost/Benefit Analysis for the ASVT on* Operational *Applications of Satellite Snow-Cover Observations,* National Aeronautics and Space Administration Technical Paper 1828, 1981

Channeled surface runoff, as occurs in rivers or streams, is of three major types: perennial runoff, which flows throughout the year; intermittent runoff, which occurs each year during certain seasons; and ephemeral runoff, which only occurs following an event such as a heavy rainstorm, While both intermittent and ephemeral runoff contribute at times to the flow of the perennial rivers and streams of the region, they do not constitute a dependable water-supply source, except for specialized local uses. Intermittent and ephemeral runoff characterize much of the valleys and plains of the Western United States, while the perennial rivers almost always have their headwaters in the mountain ranges of the region. The amount of ET will be determined by the amount of available energy required by this process, the seasonal distribution and amount of precipitation, and the nature of density of the vegetal cover,

The ratio between the amount of precipitation falling on a watershed and the amount leaving the watershed as surface runoff determines the “runoff efficiency” of that watershed. As the runoff efficiency increases, greater amounts of precipitation become surface runoff. Runoff efficiency for any given watershed is determined by complex interactions among precipitation, evaporation, and soil-moisture recharge. The demands of evaporation and soil moisture recharge, which must be met before any surface runoff can occur, are relatively constant from year to year, while precipitation may be variable. The interactions among these hydrologic elements are complex and generally small percentage changes in a single element, such as precipitation, will not translate directly into a proportional change in surface runoff. Runoff efficiency in the Western United States varies greatly, from as little as 10 percent in a hot desert environment (where most of the precipitation rapidly evaporates) to as much as 90 percent in a humid maritime climate. Technologies designed to increase surface runoff by changing some element of the hydrologic cycle to increase runoff efficiency must be considered in terms of the wide range of hydrologic regimes which characterized the region.

Any volume of additional runoff produced by modification of a particular watershed will eventually move through the entire river system to the sea or ground water, or be removed by evapotranspiration. The ability to measure any increased volume by the application of technology will diminish as one moves farther from the point of application and as the water is incorporated into the normal, increasing volume of the river system. Thus, the impact of the application of any watershed-management technology that produces additional surface runoff will be most easily measured near the point of application.

Information on impacts of watershed-management technologies that attempt to increase usable runoff or to improve management of that runoff has been derived largely from experimental watersheds, These technologies include: 1) precipitation augmentation by weather modification (cloud seeding), 2) removal or replacement of vegetation to reduce evapotranspiration or to increase snow captured onsite, 3] management of surface water runoff through modification of the surface permeability and landscape to store water or direct it to selected areas, and 4) water-supply forecasting, The impacts of any technology designed to alter the hydrologic cycle within a watershed will be affected by the basin's preexisting water regime, the relationship among the elements of the basin's hydrologic cycle, and the portion of the watershed to which they are applied.

It is useful to consider the major elements of a watershed in order to understand the kinds of specific technologies that might be applicable to increase surface runoff or to improve the ability to manage or forecast the natural or modified runoff. A number of classification systems have been proposed. For timbered watersheds, the U.S. Forest Service has proposed a classification scheme based on the dominant vegetation present (e. g., 14). A similar concept, based on vegetation type, has been used to describe rangeland watersheds where brush or grasses, rather than timber, are dominant (e.g., 11), For development of streamflow runoff forecast models, classification is commonly based on the dominant form of precipitation—i.e., rain or snow—while weather-modification technologies are generally classified in terms of the dominant meteorological process controlling precipitation. Fundamentally, each technology has developed its own approach to the classification of watersheds without reference to the other relevant watershed-management technologies.

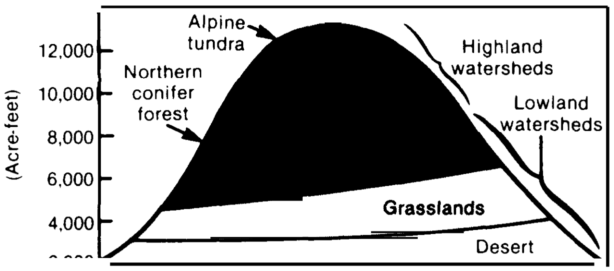
To compare technologies that modify or forecast runoff from watersheds, a simple but useful classification based *on* altitude above sea level and major topographic features was used in this assessment. In this scheme, watersheds of the Western United States may be viewed as being either "highland" watersheds, those associated with the mountain ranges of the region, or "lowland" watersheds, which are found primarily in the adjacent valleys and plains. While such a system does not completely describe the range of application for any single technology, it enables comparisons between the technologies considered. In addition, it corresponds approximately to the most recent classification scheme proposed by the Forest Service for delineating the ecoregions of the United States (3).

The highland-lowland classification used here is based primarily on major terrain features and vegetation types. In essence, the highland watersheds are located in mountain ranges and have a vegetative cover characterized by alpine tundra at their highest elevations and montane coniferous forests at lower elevations, Lowland watersheds consist of valleys and plains adjacent to these mountains. Some conifers, such as pinyon-juniper stands may be present in the lowlands, but the dominant vegetation is deciduous trees or brush and grasslands (figs. 31 and 32).

Latitude and position on the continent affect the type and density of the vegetative cover in both types of watersheds. The highland watersheds are marine, as in the Pacific Northwest; mediterranean, as in California; or continental, as in the Rocky Mountains. Lowland watersheds are prairie, in the eastern portion of the Western United States; steppe, between the Coastal Ranges and the Rocky Mountains and immediately to the east of the Rocky Mountains; or desert, in the Southwestern United States (fig, 33). In each case, a distinctive

Figure 31.—Vegetation Zones in the Mountains and Plains of Western North America

This diagram shows general conditions that might be expected in the Central Rockies of Utah. To the north, south, east, or west of this region, vegetation may change. For example, to the north and east, the pinyon-juniper zone is absent; in the east, an oak-mountain mahogany zone is present between the grassland and northern conifer forest.



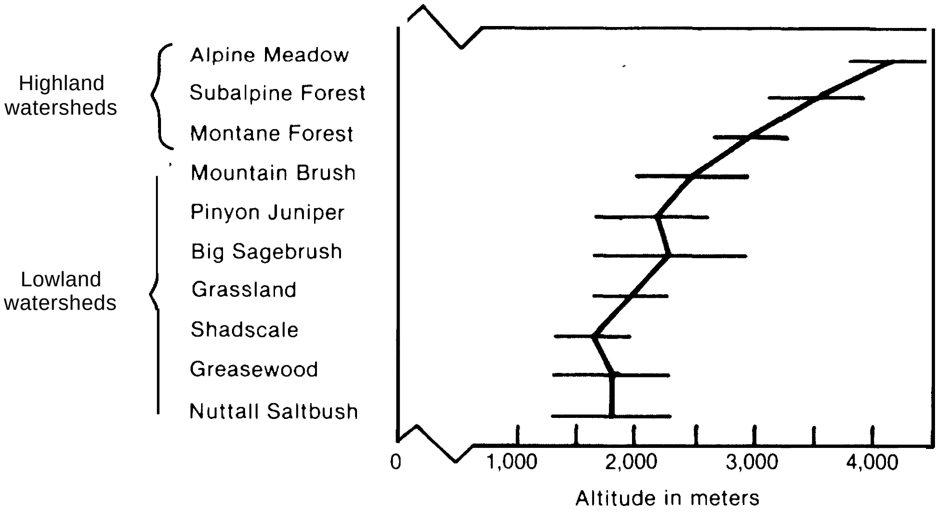
SOURCE Biological Sciences Curriculum Study, Biological Sciences: *An Ecological Approach*, BSCS Green Version, 4th ed (Chicago Rand McNally & Co 1978)

vegetation type and hydrologic regime have developed in response to precipitation and temperature patterns (3),

A highland-lowland distinction is useful in relating both the form and seasonal hydrologic behavior of water and the varied environments. The highland portion of each watershed is cold and humid relative to the surrounding lowlands. Much of the annual precipitation falls as snow during winter and becomes liquid water for runoff, evapotranspiration, or infiltration into the soil during spring and summer, The lowland portion of each watershed is warmer and drier. Rain is much more common here and snow melts more quickly during the winter or early spring than in the highlands. Snow does not accumulate to the depths common in highland areas. Generally, the amount of precipitation of any form decreases with decreasing altitude.

Highland watersheds generally give rise to perennial streams or rivers. Lowland watersheds are characterized more often by either intermittent or ephemeral runoff, While both forms of runoff are variable to some extent, both seasonally and annually, perennial streams will be less so. In addition, perennial streams and rivers are more likely to be regionally significant in their importance as water-supply sources, while intermittent and ephemeral streams are more likely to have a local, site-specific importance, Technologies to affect surface runoff must be designed with these characteristics in mind.

Figure 32.—Approximate Aptitudinal Ranges of Major Vegetation Types in the Upper **Colorado River Basin (water** resources region 14)

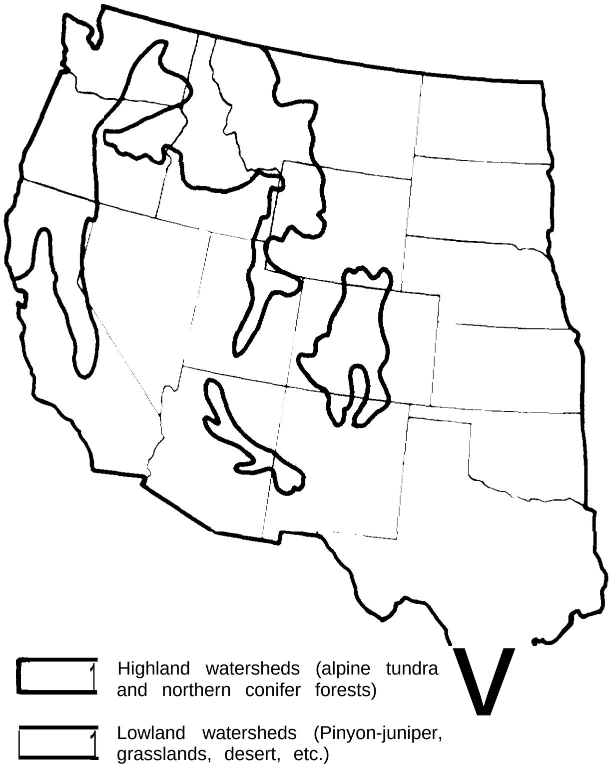


The diagram shows the various ecological communities contained within highland and lowland watersheds.

SOURCE F Branson, G Gifford, K Renard, and R Hadley, Range/and *Hydrology,* Society for Range Management, Range Science Series No 1 (Dubuque, Iowa" Kendall/Hunt Publishing Co , 1981)

Figure 33.—The Spatial Distribution of Highland and Lowland Watersheds Over the Western United States

Highland watersheds are primarily mountains and consist of northern conifers or alpine tundra biomes. Lowland watersheds are characterized by a variety of grasslands or shrub ecological communities



SOURCE: H. Anderson, M. Hoover, and K. Reinhart, "Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Supply," *USDA Forest Service General Technical Rpt. PSW-18*, pp. 82-87, 1976

The major biophysical environments that may be present in combination or singly in a watershed are the: 1) alpine tundra, 2) montane forest, and 3) grasslands or shrublands. The alpine tundra is that portion of a mountain range above timberline (the upper limit where tree growth occurs) and is found in most major mountain ranges of the Western United States. The montane forest environment extends from the timberline at the lower edge of the alpine zone to the base of the mountain. Grasslands and shrublands exist on the low-altitude plains and hills extending out from the foot of the mountains. Across these three environments, various land use practices, including timber harvesting, rangeland agriculture, or crop production, mav be practiced in some combination. In general. the annual snow/rain ratio and runoff efficiency will decrease from the alpine environment to the grasslands.

The choice of an appropriate watershed-management technology to affect surface runoff is influenced by all these watershed factors. The appropriate technology should be designed for the principal form of precipitation and the percent of surface area in each of the major biophysical environments affected. Transition zones may occur where the snow/rain precipitation ratio or biophysical environments are mixed. In these areas, no single technology may be clearly preferred, Generally, technologies that have been developed to affect surface runoff for onsite or offsite use are specific to a particular set of characteristics in highland or lowland watersheds.

The highland and lowland watersheds, primary water-producing areas of the West, largely are on public lands, As such, Federal agencies responsible for managing these lands will play an important role in affecting the future of water use on arid/semiarid lands, whether through active or passive involvement, Pursuant to their multiple-use responsibilities, these agencies have the mandate to include water resources and water-resources management within their multiple-use objectives, The multiple-use concept already is embodied in a number of Federal laws including the Multiple-Use, Sustained-Yield Act of 1960 (Public Law 86-517) and the Federal Land Policy and Management Act of 1976 (public Law 94-579). Existing multiple-use statutory guidelines prohibit optimization of a single measurable resource (e.g., timber and cows) at the expense of less quantifiable uses (e. g., watershed and recreation), and they forbid practices that impair continued land productivity (9).

Photo credit: USDA-Soil Conservation Service

Watersheds in the Western United States may be either "highland" areas, consisting of the major mountain ranges of the region, or "lowlands," the surrounding plains and valleys. Highland watersheds consist of montane forests and, above them to the summits of the ranges, the alpine zone. Lowland watersheds are characterized by sparcer forests, shrublands, or grasslands

THE TECHNOLOGIES

Weather Modification

Introduction

Weather-modification technologies, often called "cloud seeding, " owe their scientific beginning to one initial experiment that demonstrated that an artificial ice-nucleating agent such as solid carbon dioxide induces the formation of ice crystals in air supersaturated with water vapor with respect to ice (19). The ice crystals grow quickly to precipitable size and fall from the cloud as precipitation that might not have occurred naturally. All modern cloud-seeding technologies have developed from this discovery.

Cloud seeding works in two ways. First, artificial nuclei may stimulate small cloud particles to coalesce. Second, cloud seeding with ice nuclei or solid carbon dioxide (dry ice) may induce freezing and cause the production of large numbers of ice particles, which proceed to grow to precipitable size. In the first case, known as “warm seeding,” waterdrops maybe introduced into a cloud to start a process that might otherwise take longer. Because modifying a cloud might entail a substantial mass of water in the form of individual drops, finely divided salt or a water-attracting chemical mist is usually used instead. In experiments, for example, a concentrated water solution of ammonium nitrate and urea has been sprayed from an aircraft into a cloud in the form of droplets about 0.20 millimeters (mm) in diameter. Within a minute, the nitrate and urea droplets grew by gathering condensation from the vapor to a ().5()-mm size, a factor of 15 in mass. The 0.50 mm drops were large enough to start a process that may have produced drops 5 mm in diameter only 20 minutes later,

The second method, seeding by dry ice or silver iodide, requires that the clouds being seeded be at temperatures below freezing. If dry ice is used, it has the effect of inducing a massive, rapid cooling that freezes the supercooled water droplets in the cloud. In contrast, silver iodide particles are good nuclei for ice formation because of the close resemblance of their crystal structure to that of ice (21), Whichever seeding material is used, the result is the production of ice crystals that, it is argued, will increase the precipitation efficiency of air masses known to contain significant amounts of supercooled water droplets.

Water-attracting particles and ice nuclei can be introduced into the air mass in different ways. In the first field experiments, dry ice was dispersed from a small airplane (19) and silver iodide was generated at the ground. Ground-based generators are considered to be effective in the absence of a strong temperature inversion, which inhibits convection, and in mountainous terrain, where orographic processes are generally present. Silver iodide is also often released from aircraft with the aim of placing the nucleating agent directly into selected portions of clouds containing liquid droplets.

Cloud-seeding technologies have been tested primarily in two major air mass types: 1] winter orographic air masses, and 2) summer cumulus air masses. Orographic air masses are those that are forced to rise by their passage across mountain ranges and are often associated with major winter frontal systems. Cumulus air masses are those that commonly form during the summer months as warm moist air rises owing to surface solar heating, though they may also occur in post-frontal situations in winter, The seeding of orographic air masses generally is undertaken to increase the amount of snow stored in the highland mountain watersheds during the winter. Seeding cumulus clouds to increase precipitation has the primary objectives of increasing soil water, of inhibiting hail formation in lowland watersheds during the summer, or for direct crop rainfall in areas of small grains, corn, and so}’bean production.

APPLICATION TO MOUNTAIN CLOUD SYSTEMS

Three decades ago, Bergeron (4) concluded that the main potential for causing considerable artificial precipitation might be found within certain types of air masses as they are forced to rise over mountain ranges. This conclusion was based on the argument that there was more water in the clouds than was being released as precipitation. Considerations assumed a steady and often substantial formation of liquid water for an extended period of time in a fixed location and the probable accumulation of “releasable but unreleased” cloud water at levels with temperatures below 00 C. Generally, the basic criterion for determining whether or not a seeding potential exists is the natural precipitation efficiency of the clouds—orographic or otherwise. The measure of precipitation efficiency is the percentage of the total water in the cloud system that actually reaches the ground. Seeding would not be required where the efficiency is high, On the other hand, seeding may or may not be of value when the natural precipitation efficiency is low.

While precise numerical values are difficult to achieve, a useful basis for evaluating precipitation efficiency is the comparison *between* water removal by growth of ice crystals and the supply of liquid water in the cloud. To illustrate this idea, the following processes have been compared for a broad range of cloud temperatures: the average rate of formation of liquid water, the average rate of consumption of this cloud water by ice-crystal growth that would occur from natural concentrations of primary ice crystals, and actual average rates of precipitation observed at ground level. Studies show that, with cloud-top temperatures of –20 o C or colder, the observed actual precipitation corresponds closely to the rate at which liquid water becomes available in the clouds. In the main, such clouds should have a high natural precipitation efficiency with little corresponding potential for seeding.

When cloud-top temperatures are warmer than –20 °C, natural precipitation efficiency should be low. For these cases, observed values of ground precipitation are, in fact, much less than the average amount of condensate available. A potential for seeding can exist in these cases.

APPLICATION TO CUMULUS CLOUDS

In summer in the Western United States, precipitation very often occurs from cumulus clouds. These clouds form as warm moist air rises from the heated earth and are not necessarily associated with large-scale frontal systems. The natural precipitation efficiency of these isolated clouds is quite low. Even the largest clouds—those reaching thunderstorm size—exhibit precipitation efficiencies of only about 10 percent. The important question is whether isolated cumuli constitute promising targets for artificial nucleation by virtue of their comparatively low natural precipitation efficiency. A major difficulty in assessing possible modification potential is the enormous natural fluctuation in all variables.

In determining seeding potential, it has proven useful to subdivide all cumulus clouds into two types: first, those having typically 50 to 100 droplets per cubic centimeter (cm^3) and, second, those with 400 to 1,000 droplets per cm^3. As the total cloud liquid-water contents are not greatly different for the two types, the average droplet radius must be about twice as great in the first as in the second. The clouds with larger droplets have a more rapid coalescence process because fewer collisions will be required to produce a raindrop. In cumuli containing small droplets, the coalescence process would have to operate for a much longer time in order to develop raindrops in sizes large enough to precipitate. On the basis of this, ice nucleants probably offer less potential for stimulating precipitation in cumuli containing large droplets, for such cumuli can, and evidently do, develop rapidly to the precipitation stage naturally. On the other hand, the same picture suggests that cumuli containing many small droplets might be more readily modified artificially by accelerating cloud particulate growth by seeding. This assumes that these cumuli have cloud-top temperatures of less than 00 C and that natural ice-forming nuclei are so deficient that a substantial part of the cloud water is supercooled,

Although this idea seems simple, there have been few experiments that have demonstrated the effect in the field. Early observational programs, such as those in Australia, gave clear-cut results (23), whereas a U.S. study was inconclusive. It is estimated that an operational cumulus cloud-seeding program (e.g., in the high plains) would require a minimum of 10 years, starting from existing knowledge based on a focused and adequately supported effort (25). *

Several States, local government agencies, and private utility companies now are engaged in weather-modification projects in the Western United States. In addition, ongoing and planned large-scale cooperative programs exist under Bureau of Reclamation sponsorship as well as jointly funded cooperative programs with the National Oceanic and Atmospheric Administration (NOAA) (22).

As of 1982, the States in which seeding projects were being conducted were California, Nevada, Utah, North Dakota, and Texas, with planning under way in Colorado, Oklahoma,

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*Seeding very large cumulus and cumulonimbus clouds has been undertaken in Kenya, U. S. S. R., Switzerland, France, Canada, and the United States in attempts to decrease damage from hail. Some of these programs claim 30- to 80-percent decreases in hail damage to crops. Others have observed no effects.

and Arizona. There are 13 independent project areas in California, 4 in Nevada, 3 in Utah, 3 in North Dakota, 2 in Colorado, and 1 in Texas. Most, if not all, of the programs west of the Continental Divide are conducted in high mountainous areas where snowpack augmentation is the goal. The programs east of the Divide are designed for rain enhancement and/or hail suppression efforts (22).

SEEDABILITY POTENTIAL

For the Western States, the potential of weather modification for augmenting water supplies is related, in part, to the number of opportunities available for a seeding operation. The fall, winter, and spring months yield between 30 and 50 precipitation events in which opportunities may exist to carry out a modification operation. An event is defined as a storm that is expected to last 6 hours or more and to yield measurable precipitation. Some of these storm events may last up to 3 days. The potential for seeding a storm to produce additional precipitation depends on the existence of supercooled liquid water in the clouds of that storm. The cloud must contain liquid water at temperatures below freezing for the ice phase processes to be effective. If there are only a few "seedable" events available per season at any given location, considerations of economics may become crucial in deciding on the benefits to be accrued from this opportunity-limited situation (22).

"AREA OF EFFECT" PROBLEM

One of the most important issues in weather modification today is the determination of the ''area of effect" of operational and/or research cloud-seeding programs. In its fullest sense, area of effect encompasses not only the microphysical and dynamic aspects of cloud-seeding effects but questions of water budgets, optimization of seeding technology, and State and international boundary issues.

In particular, it is important for the research community to determine the impact (if any) of seeding programs in one State on the water supplies of an adjacent State or area. It is well known that in a number of weather-modification projects, there have been indications of noticeable effects outside the "intended target areas, sometimes at surprisingly large distances, especially in the downwind direction. The programs in Switzerland, Israel, and Colorado, in particular, have been cited as examples (22),

RIGHTS TO USE Of AUGMENTED WATER

Perhaps no other aspect of weather modification is as perplexing as the concept of ownership or use rights regarding the water generated by cloud-seeding projects. No body of law exists to deal with such problems; laws were created to deal with surface waters and were later expanded to cover ground water. Stretching these earth-bound laws to cover atmospheric moisture that does not confine itself to a watershed, let alone to political boundaries, is a difficult process (10).

The principal questions for weather modifiers relate to the share of "new" water that might go to each modifier and the verification of water-use rights based on weather-modification activity. The questions become increasingly complex as possible variables are considered—Does a senior rightholder downstream have any rights to the "new" water in dry years? IS a Federal water right created for water that the U.S. Government generates through its cloud-seeding efforts? Answers to questions such as these will depend on how the new water is classified. Classification hinges conceptually on identifying the water as ''developed" water—i.e., water not previously a part of the natural yield of a river basin but rather additional water made available from the weather modification activities.

It is essential that the weather modifier be able to prove that additional runoff has actually been developed before securing a right to its use. It is likely that the procedure would require the modifier to demonstrate that a specific quantity of water in the stream would not have been there under normal conditions—i,e,, without cloud seeding,

The problem is narrowed to that of "proving" a quantifiable increase over the natural streamflow. Eventually, the technology may be developed to enable definitive and accurate measurement of such increases, but it is not possible now, as discussed earlier, and a great deal more knowledge must be available before anyone can define how much water is developed from cloud seeding. Until the science of weather modification offers some concrete proof of its effectiveness and measures this effectiveness, any precipitation so produced almost certainly will be considered part of the natural yield and will be distributed in accordance with established rights.

Assessment

Compared to other augmentation technologies such as evaporation control or interbasin transfer, the technology of weather modification can be viewed as an economically attractive method for bringing additional water into water-short regions of the Western United States. However, the viability of the technology rests on the occurrence of suitable atmospheric conditions in these regions. Drought years are the result of low rainfall, an indication of a low frequency of precipitating cloud systems. Weather-modification technology depends on the availability of suitable cloud conditions for its application. Consequently, the high, mountainous regions of the Western United States probably offer the greatest and most reliable potential for precipitation augmentation because these regions receive the winter snows and thus provide the springtime runoff water supplies to agricultural lands and to ground water. These highland regions are cooler for longer periods of time than lowlands and thus provide a longer season for accumulation of snow and storage of water as snow.

In general, the major difficulty faced in weather-modification technologies is the inability to detect statistically significant changes in either snowpack water-equivalent depths, snowmelt runoff, decreased hailstone size, or increased rainfall at the ground surface. While fairly substantial increases in the volume of water stored in the winter snowpack have been claimed, these claims have been challenged by other researchers. In at least one case (" Project Skywater, " San Juan Mountains, southwestern Colorado), after a number of years of experimental seeding operations, the Bureau of Reclamation concluded that a slight, but statistically insignificant, *decrease* in streamflow had occurred.

These discrepancies may be due, in part, to an incomplete understanding of snow-crystal or hailstone growth and the precipitation processes involved, Also a contributing factor is the incomplete understanding of the processes affecting snowpack accumulation, melt, and runoff in the mountain environment. There are problems in selecting suitable air masses and in understanding both the physical processes that control the natural production of ice nuclei and the efficiency of the nucleation process. Similarly, the way in which seeding materials are dispersed in air masses, the origin and location of supercooled water in air masses, and the effects of small changes in the purity of seeding agents need further study. The definition of useful verification standards is another major area needing attention,

The most valid line of research, in light of these problems, may involve studies of air mass characteristics to understand better the nature and behavior of an air mass prior to and during a seeding experiment. Attempts are now underway to develop more objective verification procedures based on properties of the deposited snow rather than on statistical relationships between precipitation and runoff. More sophisticated studies of the mountain snow accumulation and runoff regimes must be an integral part of future cloud-seeding experiments.

The environmental effects of increased precipitation as a result of cloud seeding have been examined on a number of occasions. Short-term environmental effects are discussed in the Colorado River Basin Pilot Project Final Environmental Statement, The Project Skywater Programmatic Final Environmental Statement, and the Sierra Cooperative Pilot Project Environmental Assessment (22), These studies conclude that the incremental increases in precipitation over the short term involved with cloud-seeding research programs do not have significant adverse impacts on environmental-ecological systems. Incremental increases are usually within the historic natural variability of seasonal and annual precipitation in the study areas (22). As additional information and experience have become available, scientific concerns about potential long-term negative environmental impacts caused by precipitation augmentation have eased (22).

Surface Watershed Management

While precipitation augmentation through cloud seeding may be considered a watershed-management technology, current use of this term restricts it to those practices designed to modify the volume or timing of surface runoff by surface modifications, such as vegetation manipulation. This section discusses technologies that attempt to increase surface runoff for offsite use or to retain precipitation onsite to promote plant growth and stabilize the soil. The technologies will be discussed in the context of the watersheds they affect.

In general, technologies that have been developed to affect surface runoff by surface modification are site-specific in both highland and lowland watersheds. Transitional zones also exist where the hydrologic environment is a mixture of montane forests and alpine tundra (at the upper limit) or grasslands and brushlands (at the lower). In addition a mixture of precipitation can occur in each watershed type, depending on elevation. In transition zones, technologies from either highland or lowland watersheds may be applicable, and careful evaluation is necessary for selecting the appropriate technology for a particular transition zone.

Highland Watersheds

Typically, highland watersheds are composed of two biophysical environments or zones: the unlimbered alpine belt above timberline and, below this, the montane forests. These two zones are commonly separated by a transitional zone which most workers refer to as the “subalpine. ” Surface runoff, ground water recharge (where it occurs), and the liquid water necessary for plant growth is supplied largely by the melting of the snowpack that forms during the winter.

Highland watersheds play a vital role in supplying water to rivers in the Western States. The percentage of total surface runoff passing annually through a river or stream which originates from the melting of the snowpack of highland watersheds varies widely; however, for the 11 westernmost States, researchers estimate that between 70 to 75 percent of the total annual surface runoff of the region originates from this source (e.g., 7).

In addition to their importance as water-yielding areas, highland watersheds have many other uses. Domestic and wild animals graze in the grasslands of the alpine belt and in meadows within the montane belt. In the montane forests, commercial timber production is the ‘most important. Other potential or actual uses include recreation, wildlife habitat and, locally, mineral extraction.

THE ALPINE ZONE

Introduction.—The alpine zone is a relatively cold, wet environment, where precipitation falls as snow during every month of the year and snow deposits persist throughout the year. Precipitation amounts, which commonly increase with elevation, are highest in the alpine zone. Coupled with the low amounts of evapotranspiration and infiltration, the alpine regions produce the highest runoff efficiency (the ratio between precipitation inputs and streamflow) in the West,

The snowcover of the alpine zone is unevenly distributed, a result of high winds that often accompany the storms moving across the region and the rugged topography, which traps blowing snow. Large areas blown completely free of snow alternate with deep snowdrifts that form in sheltered sites, The concentration of snow into these snowdrifts causes snowmelt to be delayed relative to areas where snow deposits are more uniform. This, in turn, delays runoff until later in the season than is the case with the snow cover at lower altitudes. It is this storage and delay of snow melt runoff until the warmer summer months, when demand in the lowlands is at a maximum, which contribute to the hydrologic importance of the alpine belt,

The alpine zone is not uniformly distributed throughout the mountain ranges of the Western United States. Estimates of its total surface area are difficult to make. One estimate places the total alpine acreage in the West at approximately 10 million acres (20), or slightly less than 10 percent of the acreage of montane forests in the region. A more recent estimate suggests that the actual area may be closer to 8 million acres.

Hydrologic studies in the alpine region of the Western United States have been scattered and sporadic, Studies specifically dealing with aspects of the hydrologic cycle as they influence snow accumulation, melt, and runoff in the alpine belt have been undertaken by only a few investigators, and only broad generalizations are possible from these studies.

Existing research indicates that the alpine region is naturally efficient in producing runoff and constitutes an important water source for the region. For example, in Colorado, estimates indicate that the alpine belt, which comprises about 3.5 percent of the surface area of the State, produces approximately 20 percent of the State's surface runoff (20). In Utah, it is estimated that 10 percent of the State's highest elevation areas yield 60 percent of its runoff; this area and the next lower 15 percent of the surface area, account for 90 percent of the total runoff of the State (20).

Relatively few technologies have been proposed for manipulating runoff and water yield in the alpine belt. In part, this is because of the difficulties of access to and movement in an environment that generally is cold, windy, and snow covered during much of the year. Additionally, research in this environment has had little funding support from the public and private sector, owing to the apparent lack of management opportunities. Studies to date have focused primarily on the installation of snow fences to trap blowing snow, to increase local snow storage, and to reduce water losses from sublimation during wind transport (16). Other studies have looked at the possibilities of rehabilitating parts of alpine watersheds that are disturbed by other activities, such as mining (13).

Assessment.—A major limitation for application of snow-fencing technologies in the alpine zone is the scarcity of favorable sites for installation of fences. Suitable sites constitute a small fraction of the total alpine area (6).

Research indicates that some potential exists for rehabilitating many presently disturbed alpine sites, but only more intensive management practices can help reduce the impacts of future disturbances (13), Severely affected sites, such as abandoned or active mine dumps, generally require intensive revegetation and rehabilitation efforts. The success of these efforts requires an extensive commitment of manpower, money, and expanded basic and applied research programs.

Two major considerations affect any management activities in the alpine, First, because of the apparent high natural runoff efficiency, the alpine may be most productive in yielding water through passive management rather than through the application of manipulative technologies. Second, a conservative approach to the development of nonwater resources may be the most prudent course until a better understanding of the hydrologic significance of this environment is obtained. Future environmental problems may become more severe as the result of other human activities on the alpine zone—e.g., mining, grazing, and recreational uses (table 37), Eventually, these kinds of activities may in turn affect the quality and quantity of runoff produced in that zone (13),

THE MONTANE ZONE

Introduction.—The montane zone generally extends downward from the timberline to the foot of the mountain ranges. Its vegetation is largely coniferous forest, but the types of trees and their spacing vary in a complex fashion with latitude and altitude, The dominant precipitation form is winter snow. The headwaters of eight of the nine major water re-

Table 37.—Summary of the Nature and Extent of Alpine Disturbances in the Western United States as of 1976

	Extent of disturbance		
Nature of disturbance	Hectares	Acres	Percent of total disturbed
Grazing	256,194	633,056	74.5
Recreation	38,140	94,244	11,1
Mining	34,677	85,686	10.1
Roads	12,748	31,499	3.7
Pipelines	683	1,689	0.2
Power lines	289	714	0.1
Reservoirs	274	676	0.1
Other	795	1,964	0.2
Total disturbance	343,800	849,528	100.0
Total area of alpine	2,915,951	7,205,315	—
Percent disturbed	11.8	11.8	—
Additional anticipated by 1980	57,646	142,444	16.7a

aBased on the 1976 total

SOURCE R Johnston and R Brown, 'Hydrologic Aspects Related to the Management of Alpine Areas" USDA reprint from *Special Management Needs of Alpine Ecosystems* Intermountain Forest and Range Experiment Stat Ion Ogden, Utah, 1979

source regions of the Western United States lie in this zone (see ch, III).

About 120 million acres of the Rocky Mountains lie within the montane zone. Snow water-equivalent accumulation depths in this area at the end of the winter average about 2.5 ft annually, or approximately 320 million acre-ft of water (6). In the Cascade/Sierra Ranges, the other major mountain chain of the Western United States, approximately 30 million acres lie within the montane zone (2).

Experimental research dealing with the relationship between forests and surface streamflow has been conducted for at least 100 years (17). The first recorded U.S. experimental study of the effects of forest removal as a planned land-use change on streamflow started in 1910 at Wagon Wheel Gap, Colo. By the 1960's, work accelerated on the potential for water production through timber-removal techniques in the montane zone [2,14). Some 200 forested experimental watersheds were under study throughout the United States by 1960. In the Western United States, at least six experimental watershed areas have been instrumented and studied for water production. These experimental watersheds located in Arizona, California, Colorado, and Oregon, represent a variety of hydrologic environments (2).

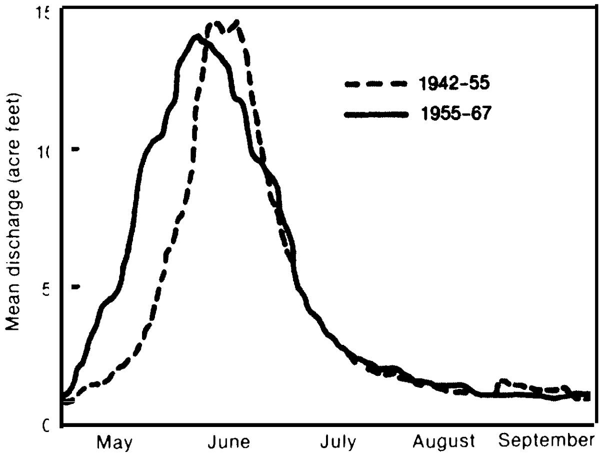
Almost all experimental work on water-production technologies in these watersheds has been conducted by the U.S. Forest Service, the Federal agency responsible for management of most montane areas in the Western United States. Most work has involved timber removal, either through clearcutting, patch-cutting, or thinning. Clearcutting is a procedure that totally removes forest cover and may involve an entire watershed. This procedure is designed to minimize transpiration losses, Patch-cutting involves opening the forest cover in a patch or strip whose width is about three to eight times the tree height and whose area totals 30 to 50 percent of the forest area. Patch-cutting is designed to redistribute winter snowfall by concentrating it within openings for maximum capture and storage,

Assessment.—In certain situations, vegetation management through timber harvesting may produce local increases in water yield. Application of this technology to increase surface runoff has generally been restricted to experimental watersheds. Work remains to be done on its general application and value on a larger scale and to unstudied watersheds of the Western United States for purposes of supporting arid/semiarid agriculture. Also needing more attention are the extent and nature of the impacts of this technology on other major elements of the hydrologic cycle.

A number of attempts have been made by the Forest Service to estimate and predict the site-specific, water-related results of its timber removal experiments. Early evaluations of results were based on classical hydrologic methods involving paired-basin comparisons and before/after treatment studies (6). The comparisons have since been augmented by basin simulation models.

Studies of the Fool Creek basin at Fraser, Colo., have been the basis for Forest Service predictions that streamflow water yields from Rocky Mountain forests might be increased by 2 to 3 inches annually through selective patch-cutting (fig. 34) (14), In this central Colorado

Figure 34.— Average Runoff Hydrographic for Experimental Watershed



Average runoff hydrographs for a 14-year period for the Fool Creek experimental watershed in Colorado. The solid line is the runoff for the 13-year period following timber removal. Note that the primary effect was an earlier onset of spring runoff.

SOURCE Charles F. Leaf, *Watershed Management in the Central and Southern Rocky Mountains: A Summary of the Status of Our Knowledge by Vegetation Types*, USDA Forest Service Research Paper RM 142, March 1975

watershed, 40 percent of the old-growth lodgepole pine and spruce-fir forest were strip-cut in 1955. Results from experimental forest modification in the west coast montane forests have led to similar predictions (2).

Questions of whether these increases can be maintained and whether they can be detected at downstream arid/semiarid agricultural sites are important, both in terms of the technology potential and its economic feasibility for Western agriculture. The maintenance of runoff increases depends on several variables such as the amount of snow stored in drifts, the amount of sustained reduction in evaporation, natural regeneration features of the harvested area, and measures applied to control regrowth (2). For example, new plant growth may reduce surface water yield (2,20). If this hydrologic response occurs, regrowth must be controlled to sustain initial water-yield increases. Moreover, using existing stream-gaging technology, it may be difficult to detect increased yields at points downstream where arid/semiarid agriculture is practiced because such increases are relatively small when combined with the entire volume of watershed runoff at the point of use.

Application of runoff results obtained in experimental watersheds to unstudied watersheds presents other questions in view of the range of hydrologic responses possible from site to site (box K). Within unstudied watershed areas, various elements of the hydrologic cycle still are unmeasured. Inferences must be drawn and assumptions made concerning the manner in which these unmeasured variables interact. Researchers often use statistical trends of hydrologic relationships identified in studied watersheds to predict hydrologic effects from timber removal in other watersheds. These methods must be used with care because the extension of results from experimental watersheds to other areas sometimes may not be valid (17).

The meaning of experimental results regarding the relationship of timber removal and increased surface runoff remains unclear. Studies of the natural hydrologic activity of a subalpine forest in the Appalachian Mountains in the Eastern United States found that 42 percent of the total annual precipitation to that watershed was added by cloud-droplet condensation on the trees of the watershed. According to this research, if this forest vegetation were removed, total precipitation reaching the surface from that part of the watershed would be reduced and runoff would decrease. Some Russian watershed-management studies have produced results indicating that in forests where almost all annual precipitation occurs as snow, and runoff is produced primarily by the spring snowmelt, streamflow decreased as the forests were removed (17). More recent studies reported by the Forest Service tend to support the Russian results. Leaf (14) found that "[w]hen 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. "

More recently, Hawley and McCuen (12) analyzed the relationships that exist between water yield and 17 environmental variables for 605 watersheds in the Western United States, They found that the 11 westernmost States could be best represented by five hydrologic regions (fig. 35). In each of these regions, precipitation was the most important factor in determining water

Box K.—Managing Vegetation for Water Production: Perspectives From the U.S. Forest Service

A review of recent U.S. Forest Service literature that considered the possibility of using forest-management practices to increase water yields illustrates some of the complexities associated with application of this technology. According to their research (Hibbert, 1983; Kattelman, et al., 1983; Troendle, 1983; Harr, 1983; and Douglass, 1983), each of the major forest and range biomes of the United States shows potential for water-yield augmentation from forest management. For example, in the Eastern United States, scientists report that "we know how to manage forests to improve water yield and the potential for increasing the water supply is enormous" (Douglass, 1983). Similarly, in the mountainous regions of western Washington and Oregon, the potential for augmenting water yields appears high (Harr, 1983). Some potential also exists for increasing water yields by managing rangeland vegetation on watersheds where average precipitation exceeds 18 inches per year, in some regions of the Colorado Rockies, and in parts of California (Hibbert, 1983; Troendle, 1983; and Kettlemann, et al., 1983).

Notwithstanding these results, these same researchers caution that the expectation that vegetation manipulation can and will provide significant additions of water for Western agriculture may not be realized. Kattleman and associates report that the large streamflow increases demonstrated on small experimental watersheds in California's Sierra Nevada diminish rapidly when spread over a major river basin under multiple-use management. Furthermore, these researchers note that the absence of large-scale studies limits their conclusions to little more than conjecture.

This is not an isolated problem. In the Rocky Mountains, Troendle reports that the role of snowpack manipulation and evapotranspiration modification is not well defined. Moreover, Troendle adds that a watershed's capacity to store water and yield "excess" water varies across the area, and from a practical standpoint, only a small part of the watershed is now available for vegetation management, Others have concurred with this opinion. On lowland rangelands, Hibbert estimates that less than 1 percent of the Western rangelands can be managed to increase water yield and that little or no increase can be realized by eradication of low-density brush and certain woodland types. Scientists in the Pacific Northwest concluded that, realistically, watersheds will not be managed to produce more water (Harr, 1983).

SOURCES: James E. Douglass, "Potential for Water Yield Augmentation From Forest Managment in the Eastern United States," 1983. R. Dennis Harr, "Potential for Augmenting Water Yield Through Forest Practices in Western Washington and Western Oregon," 1983. Alden R. Hibbert, "'Water Yield Improvement Potential by Vegetation Management on Western Rangelands," 1983. Richard C. Kattlemann, Neil H. Berg, and John Rector, "The Potential for Increasing Streamflow From Sierra Nevada Watersheds," 1983. C. A. Troendle, "The Potential for Water Yield Augmentation From Forest Management in the Rocky Mountain Region," 1983. All of the above are in *Water Resources Bulletin 19,* **in press.**

yields, followed by elevation and air temperature. Land-use variables, including vegetation cover density, did not correlate well with water yield. For purposes of predicting water yield from a Western watershed, vegetation cover density "did not significantly improve the accuracy of the estimates where the precipitation, elevation, and temperature variables were also used in the estimation equation. "

Such studies as these underscore the need for additional research before timber removal from the Western montane is a generally acceptable technology to increase water supplies for downstream arid/semiarid agriculture. At some sites it may be difficult to determine with any certainty the short-term effects of timber removal on the hydrologic activity of the various components affecting the arid/semiarid agricultural area. It may become even more difficult to determine with some degree of accuracy the long-term hydrologic effects and potentials of different watersheds for Western agriculture and development in general.

It has been suggested that the effects of timber harvest activities on soil erosion and increased sedimentation may far outweigh any beneficial effects on streamflow (8), The amount of soil erosion and sediment production that may result from timber removal will be related to local variation in climate, terrain,

Figure 35.— Regions of Hydrologic Similarity

Regions of hydrologic similarity, based on the relationship between annual runoff and precipitation, elevation, and temperature variables in the Western United States. No two regions respond i n the same way to these controls on runoff.

SOURCE M Hawley and R MuCuen 'Water Yield Estimation in Western United States," *J. Irrig. and Drainage Division Proc. A. Soc Civ Eng., 108* (No. IRI) 2534, 1981

vegetation, and the type and size of timber harvest undertaken (fig. 36). Forest Service literature indicates that most forests in the Western United States have a natural sediment yield of approximately 45 tons/mi^2/yr; logging operations have increased this annual yield to between zoo and 2,000 tons/mi^2, depending on the particular logging technology employed (2).

Cumulative environmental impacts of any regrowth control measures must also be assessed. If regrowth control involves repeated use of mechanical or chemical measures, additional environmental impacts may be created both onsite and downstream through increased chemical pollution and sedimentation.

Finally, the potential of timber-removal technologies in the montane for increasing surface runoff involves the question of scale. Opportunities for application of timber-removal technology for water production exist on a relatively small portion of the total forested acreage. A realistic expectation of the amount of additional water that could be produced in the next 50 years under a timber-removal approach to watershed management in the montane forests would be approximately 3.7 million acre-ft (2). A large but unspecified amount of this water would be produced by Western forests. This figure represents less than 1 percent of the present mean annual runoff from the 17 Western States and, as has been noted previously, would be difficult to detect by existing stream-gaging networks at distances from the modified watershed where arid/semiarid agriculture is practiced, Some question exists also regarding the desirability of extensive modification of Western surface area, especially when wilderness and other less modified, natural mountain environments are involved. A watershed-management technology that might substantially alter a minimum of 10 percent of the Western forests and may not produce a significant addition to the water needs of arid/semiarid agriculture may be difficult to justify from the point of view of agriculture.

Lowland Watersheds

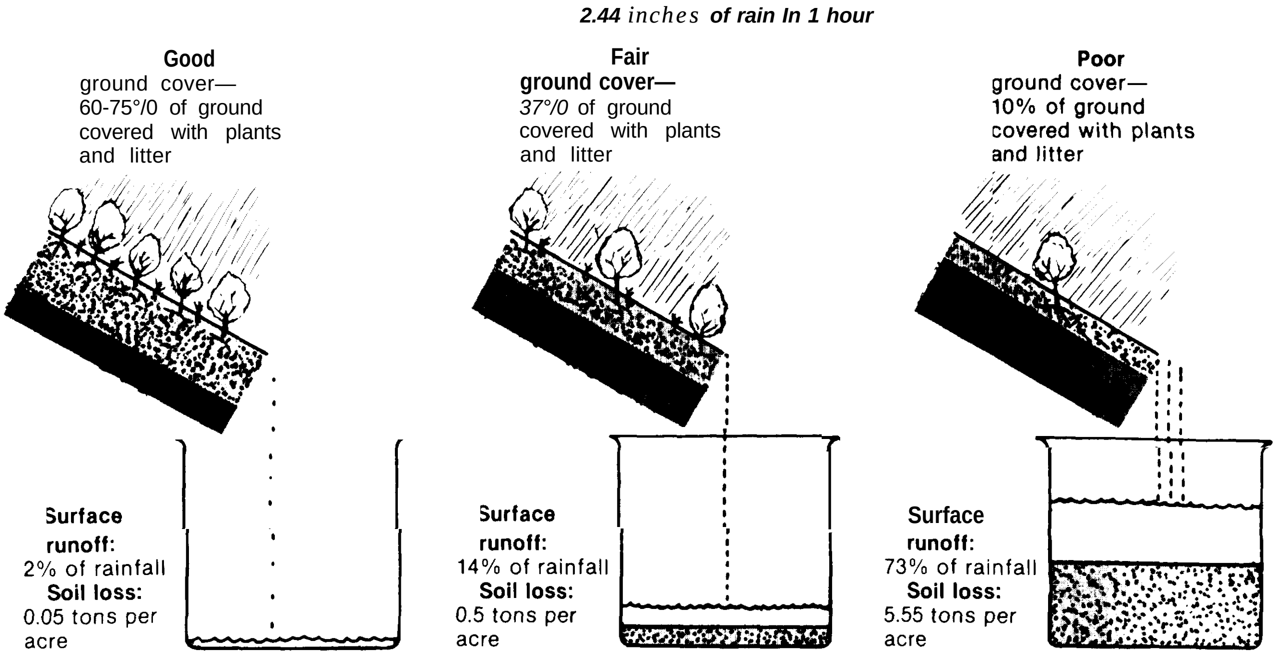
INTRODUCTION

Many lowland watersheds are used for livestock grazing and the technologies affecting surface runoff are often associated with range management. The technologies applied to lowland watersheds that are considered in this section are designed to produce additional surface runoff for offsite use. Broadly, the technologies consist of: 1) vegetation removal and replacement (brush control), and 2) runoff agriculture. Both types of technologies are used to increase water yields by facilitating a shift of water from one component of the hydrologic cycle to another.

VEGETATION REMOVAL AND REPLACEMENT (BRUSH CONTROL)

Introduction.—Much of the vegetation in lowland areas consists of grasses, forbs, and shrubs. Technologies that manipulate vegeta-

Figure 36.—The Effect of Watershed Condition on Rainstorm Runoff and Erosion



The effect of watershed condition on rainstorm runoff and erosion (average of 3 plots for each condition) on a subalpine watershed in the Great Basin experimental watershed, Utah.

SOURCE: A. Croft and R. Bailey, *Mountain Water*, Intermountain Region, U.S. Forest Service, Logan, Utah, 1964.

tion on these sites can have two purposes: 1) to increase offsite water yield by replacing deep-rooted shrubs with shallow-rooted grasses or forbs that consume less water (also see discussion of phreatophyte management in ch. VII), or 2) to increase soil water available to forage plants by controlling less palatable shrubs (see chs. IX and XI).

Vegetation removal can be accomplished in several ways, and each method has different effects on vegetation and soils. For example, mechanical brush control is used widely in some areas. Some types of mechanical brush control [e. g., hand slashing, shredding, roller chopping) remove only the top growth of the plant and result in minimal soil disturbance; others (chaining, cabling, disk plowing, grubbing, railing, bulldozing, and root plowing) remove the entire plant and can result in extensive soil disturbance. Generally, high labor and energy costs are associated with these practices, and rough terrain can limit their application.

Herbicide application can also be used to control vegetation on some shrub-dominated rangelands. Generally, herbicides have an advantage over some other brush control methods because of their relatively low costs, selectivity in control, reduced labor requirements, safety and utility in rugged terrain, maintenance of ground cover, and minimal soil disturbance (5].

A third method of brush control is by fire, the oldest known practice to manipulate vegetation. Prescribed burning is an inexpensive and often effective type of control that can be used in combination with other brush control methods for long-term brush control. However, in some cases, brush areas cannot support a fire, and because the burned land is denuded for a short period of time, the potential for erosion may be high, especially on steep land or where the soil is not firm,

Finally, vegetation can be manipulated through biological conversion or elimination, These methods employ grazing animals, insects, or pathogens to control plants. The control agent can either change plant composition directly or indirectly by reducing the vigor or reproductive ability of the target plant or by promoting disease.

Assessment.—The effects of brush control on the hydrologic characteristics of a watershed are a result of the interactions among the vegetation, the type of control used to manipulate vegetation, site characteristics (e. g., soil and slope), climatic factors (e.g., rainfall amounts and distribution and storm intensities), weather before and after application, and posttreatment practices (5). Because of the normal variability of these factors, the effects of brush control will vary naturally over time and from area to area,

To date, the evaluation of brush control on the hydrologic characteristics of watersheds has received little research attention (5). Instead, most studies have focused on livestock response or vegetation change as a result of vegetation manipulation.

Some research suggests, however, that brush control may increase offsite water yields under certain site conditions. For example, in heavy brush-infested chaparral or mesquite watersheds that receive at least 20 inches (508 mm) of precipitation each year, vegetation manipulation may increase water yields from these sites, but brush control must be maintained (5), Limited offsite water-yield increases can also be expected by converting brush to grass and forbs at the higher precipitation zones of pinyon-juniper or mountain big sagebrush watersheds. On other rangeland watersheds, however, when shrubs are replaced by grasses and forbs, the herbaceous vegetation uses the available soil moisture equally well, and little or no offsite water-yield increases can be expected.

Brush control to increase offsite water yields has been restricted to relatively small experimental sites. Many questions remain about the application of this technology on a larger scale and under different conditions (e.g., vegetation types, soil types, topography, and brush control practices). Environmental effects of these practices also require resolution. In some cases, large-scale vegetation removal could result in accelerated soil erosion and sediment production, degraded water quality, increased flood hazard, and diminished fish and wildlife habitat, Application and maintenance costs must be determined and compared to the benefits derived from their use.

The following plant communities are considered to be especially troublesome to range managers, though they are not the only plants considered problems. Rather, these examples represent some of the range plant communities where hydrologic data are available:

*Sagebrush-Dominated Rangelands.—Sage*brush-dominated rangelands are most abundant in the intermountain region, and some range managers estimate that these areas produce forage at about one-half of their potential (5). Sagebrush *(Artemisia)* is a natural component in many plant communities but readily replaces the grasses under heavy grazing pressures, Since the 1940's, a major effort has been made to clear sagebrush-dominated lands and reseed these areas to introduced grasses, such as crested wheatgrass *(Agropyron cristatum).*

Most research on sagebrush-dominated rangeland has evaluated livestock response or vegetation change as a function of brush control (5). In studies of the influence of sagebrush control on hydrologic variables, research indicates that infiltration rates, sediment production, runoff, and erosion will vary with location and type of brush control. For example, herbicide application usually has the least effect on hydrologic characteristics (5). Mechanical methods of brush control have a limited effect on offsite water yields and sediment production, depending on the degree of soil disturbance, the success of reseeding operations, and other site characteristics (5). The effect of prescribed burning on hydrologic characteristics has not been studied on sagebrush dominated rangelands. In general, research shows that sagebrush or grass vegetation use most of the available soil water, and brush control will not increase offsite water yields, although a large increase in forage production can be expected.

Pinyon-Juniper Dominated Rangelands.— Pinyon (Pinus)-juniper (Juniperus) woodlands cover extensive areas of some watersheds in Arizona, Colorado, New Mexico, Nevada, Texas, and Utah. They occur mostly at intermediate elevations in areas receiving less than 20 inches (500 mm) of precipitation each year and usual l}' have limited commercial value. These trees intercept precipitation, which is then evaporated without reaching the ground, or consume water through transpiration that might otherwise be available for forage plants. Pinyon-juniper woodlands typically have low livestock-carrying capacities, a result, in part, of tree-stand density and of the invasion of trees into grassland.

Mechanical methods of brush control, such as slashing, bulldozing, and chaining, are the primary methods used to control this vegetation, although fire and herbicide application have also been employed. Studies that have evaluated the influence of pinyon-juniper control on watershed variables have focused mostly on offsite water-yield increases after application, Results of these treatments have varied. For example, one study of the Beaver Creek watershed in Arizona applied three different brush-control techniques (cabling, herbicide application, and hand slashing) to paired watersheds in an effort to boost water yields (5), Herbicide application significantly increased runoff, but hand slashing and chaining had little effect on runoff, possibly the result of surface modifications that trapped runoff. Based on limited sediment data, no significant change was observed in sediment yield after cabling operations or herbicide applications. Other measures of water quality (e. g., total dissolved solids, calcium, magnesium, sodium, potassium, and chloride) were lowest in herbicide-treated watersheds and highest from the cabled watershed (5),

Photo credit: USDA-Soil Conservation Service

Junipers being cleared with an anchor chain pulled by two tractors as a demonstration to develop methods to reduce clearing costs on good range sites

In another study, Wright and associates (5) studied prescribed burning of bulldozed ashe juniper *(Juniperus ashei)* on six paired micro-watersheds (0.02 to 0.19 ha) in west-central Texas and found significantly increased runoff and soil erosion on moderate and steep slopes. Controlling pinyon-juniper on gentle slopes (1 to 4 percent) had minor effects on water yields and soil erosion. Sediment loss continued on the moderate and steep slopes until vegetation and mulch cover reached about 70 percent, a period of about 9 to 15 months on moderately steep watershed and 15 to 18 months for the steep watershed.

Chaparral-Dominated Rangelands.—Chaparral refers to dense stands of shrubby plants dominated by broadleaf and narrowleaf, non-deciduous species, many of which vigorously sprout following removal of the aboveground parts. Chaparral is common to the Southwest and California and is characterized by shrubs such as live oaks *(Quercus),* mountain mahogany *(Cercocarpus),* manzanita *(Arctoscaphy-*10S), and ceanothus *(Ceanothus).* Watershed research in chaparral areas has been concerned with offsite water-yield increases from converting chaparral-dominated watersheds to perennial grasses or the effect of fire on erosion.

Mechanical, herbicide application, and prescribed burning have been used to control chaparral. However, many chaparral species are well adapted to fire, and this method alone is not an effective control, Mechanical control methods are often limited by terrain and are most suited to nearly level areas.

Brush control on chaparral areas that receive less than 20 inches (500 mm) of precipitation annually will result in minor or no water-yield increases (5), Where precipitation is greater, the potential for increased yields appears to be good; however, large variations in treatment response are not well understood.

Use of fire as a brush-control method in chaparral areas reduces soil protective cover, produces a water-repellent layer in the soil, and causes increased surface runoff and soil movement with relatively small storms (5). The results can increase the danger of floods, increase erosion and sediment yields, and facilitate soil slippage and landslides (5). Elevated levels of nutrients in streamflow following fire may also be associated with the high levels of erosion,

Mesquite-Dominated Rangelands.—Mesquite (Prosopis) is an aggressive competitor and often forms dense tangles of brush that reduce range forage production and accessibility to grazing animals, Many species and varieties of mesquite are recognized—e.g., honey mesquite and running mesquite,

Research on the hydrologic effects of brush control on mesquite is very limited. Where studies have been conducted, control of honey mesquite by several methods increased infiltration and either had no effect or decreased sediment production (5), When running mesquite was treated with a herbicide and then burned, infiltration rates were not significantly increased (5). Sediment production on areas subjected to the herbicide/burning treatment also tended to be reduced compared to untreated plots, possibly a result of improved grass cover on the burned site.

RUNOFF AGRICULTURE

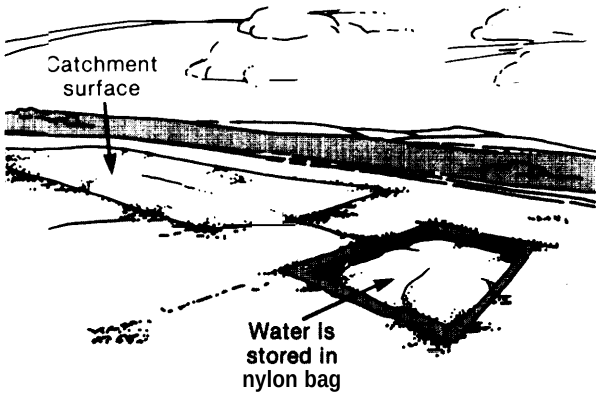
Introduction.—Because precipitation is infrequent in arid lands, farmers in lowland regions of the world have developed a variety of techniques to collect surface runoff for use in agricultural production. The theory behind these practices is that water can be collected from a large area and concentrated on a smaller, cultivated field for ample yields.

Historically, runoff agricultural systems allowed crop production in areas with as little as 4 inches of annual precipitation, When modern irrigation technology became available, many runoff agricultural systems were quickly replaced or abandoned and forgotten, Higher pumping costs for ground water, applicability to small-scale farming, availability of new building materials, and recent research on runoff agriculture have rekindled interest in the use of older technologies.

Runoff agriculture depends on water collection or "harvesting." Water-harvesting systems include two basic components: a catchment area for collecting rainwater and a water storage facility, There are many kinds of each (fig, 37). Selection of a particular method is determined by soil, topography, amount and pattern of precipitation, and climate,

Generally, water is collected on a soil surface that has been treated to make it impermeable, Treatments can include coats of paraffin wax, asphalt/fiberglass membranes, layers of sodium salts, gravel-covered plastic sheets, galvanized corrugated sheet metal, concrete slabs, or dense vegetative cover. Table 38 lists the features of some common catchment treatments,

Figure 37.— Catchment Surface With Butyl-Coated Nylon Water Storage Bag



SOURCE J L Thames and J N Fischer, "Management of Water Resources in Arid Lands, " in *Arid-land Ecosystems. Structure, Functioning and Man. agement vol 2, D W Goodall and R A Perry (ed.) Cambridge, Mass Cambridge University Press 1981), pp 519.547*

Table 38.— Potential Catchment Treatments

Treatment	Runoff efficiency (percent)	Estimated life (years)	Initial cost ($/m^2)
Land smoothing and clearing	20-35	5-1o	0.01-0.06
Water repellents	60-85	5-8	0.15-0,20
Paraffin wax	60-95	5-8	0,30-0,50
Gravel-covered sheeting	75-95	10-20	0.40-0.60
Asphalt-fabric membranes	85-95	10-20	1.25-1.75
Concrete, sheet metal, artificial rubber	60-95	10-20	3.00-5.00

SOURCE G W Frasier Water for Animals, Man and Agriculture by Water Harvesting G R Dutt C F Hutchinson and M A Garduno (eds) Rainfall *Collection for Agriculture in Arid and Semiarid* Regions (Sough. U K Commonwealth Agricultural Bureaux 1981) PP 83-86

Structures designed for other purposes, such as house roofs and roads, may collect water inadvertently, and this water can be used for agricultural purposes as well.

Collected water is stored in tanks or reservoirs. For many water-harvesting systems, the storage facilities are the more expensive item, but they are often vital to the success of a harvesting system, Typical storage facilities include butyl bags, steel tanks, and waterproof, excavated pits. It is possible that natural depressions such as playa lakes (“wet weather lakes”) or preexisting storage facilities could be used also. Stored water is diverted to irrigate fields; directed into small basins around individual trees (microcatchments); or held temporarily behind a series of terraces.

An alternative practice to the use of catchment and storage facilities is “floodwater farming, ” whereby sporadic flashfloods that occur in watercourses of arid lands are managed to

Photo credit: USDA Soil Conservation Service

Masonry and water spreaders. Stock grazing on spreading area treated with rock percolators on contour supply water for crops. For example, crops can be planted in the bottom of intermittent watercourses, and dams can be used to control water when flashfloods occur; or crops can be planted at the point where intermittent watercourses spread into an alluvial fan.

Assessment.—A variety of crops can be grown using water obtained from surface runoff. Generally, crops need to be deep-rooted, drought-resistant, and suited to local soils, climate, and precipitation, The Papago Indians, for example, grow a number of vegetables using this practice, and some crops have been bred especially for this purpose. Other possible crops are jojoba, Christmas trees, tree fruits, grains, and wine grapes, Runoff agriculture can also be used to aid in establishment of plants that will not be harvested. For example, water-harvesting technology is being used in Mexico to aid in reseeding degraded rangelands.

Runoff agriculture systems that use water-storage facilities have been used extensively for animal watering to provide dependable sources of water for livestock and wildlife when other supplies fail. Some small systems that furnish water for wildlife in remote areas have been developed on public lands. Larger systems with both large catchment areas and storage facilities can provide water for several hundred head of livestock.

With current technologies, runoff agriculture has some physical, biological, and economic limitations, The systems depend on rainfall and are no more dependable than the weather. In areas with less than 2 to 3 inches (50 to 75 mm) of annual rainfall, costs of application and operation for water catchment and storage facilities may outweigh benefits of increased crop production, In addition, the high costs of these technologies restrict its use to small-scale applications such as livestock or wildlife.

Runoff agriculture systems also vary widely in their efficiency in collecting precipitation because of differences in soil, topography, climate, pattern of precipitation, and the materials used for catchment and storage facilities. Limited experience has shown that some catchment and storage facilities can collect 20 to 40 percent of precipitation, More elaborate systems can collect more than 90 percent,

Lifespan of the soil treatments is limited also, and replacement is costly, While these have improved greatly in recent years, the least expensive treatments still must be replaced every 5 to 10 years (table 38), Maintenance is often required because poorly designed and maintained facilities can cause soil erosion or local flooding. The site-specific nature of these facilities also contributes to their high cost. Each facility must be designed for its location and intended use.

Some scientists believe that with the rise in energy costs, runoff agriculture may compete more favorably with conventional sources of water. Questions remain, however; information is needed on the application of large-scale runoff systems on conventional agricultural crops and on the more complex effects of these systems on crops. For example, with jojoba it is known that runoff farming cannot be recommended when there is danger of severe, early frosts, since ample supplies of harvested water in the fall encourage growth that is very susceptible to spring freezing.

Questions have been raised also over the long-term effects of soil treatments on soil and water resources. Information on the quality of water from areas where the soil is treated is limited; some possibility exists that water from catchments could be contaminated by materials used for waterproofing.

Sreamflow Forecasting

Introduction

Effective reservoir management requires some advance knowledge of both the timing and volume of runoff into the reservoir so that releases from the reservoir can be scheduled to meet identified demands and priorities most effectively, Runoff forecast technologies have been developed to facilitate acquisition of this knowledge.

There are two broad categories of streamflow-forecast technologies. First, some technologies forecast runoff resulting from rainfall by combining meteorological forecasting, soil-moisture accounting, and flow routing. Second, some technologies forecast spring snowmelt runoff from mountain watersheds. These involve an evaluation of the amount of snow present each spring at the beginning of the melt season, how the snow melts, and the way it enters the river system.

Technologies that forecast spring runoff are particularly important in light of the major role of this water source in meeting Western water demands. A variety of approaches to forecasting runoff from melting mountain snowpacks has been developed by Federal and State agencies responsible for various aspects of water resource development or management in the West, However, comparative analyses of these approaches are rare. Much of the following is adapted from Lettenmaier, et al. [15].

In the arid interior of the West, developers of the earliest water projects saw the potential for using winter snow depth measurements in the mountains as an indirect indicator, or "index," of runoff to be expected during the spring and summer snowmelt period. By the 1930's, a network of snow-measurement stations was established, With the expansion of the data base over time, forecasting methods have used an increasing number of indirect index indicators for predicting runoff—e.g., snow-course readings (the average of 10 individual measurements of a single site), winter precipitation at low-elevation stations, soil-moisture measurements, and areal extent of snow cover. In each case, attempts were made to relate statistically some easily measured variable, such as the water content of the snowpack at a point, to the complex of interactions that determined the volume and timing of spring snowmelt runoff.

With the advent of the digital computer, the level of detail that could be considered by numerical models of snowmelt and runoff physical processes was vastly increased. This prompted the development of simulation models of runoff and later of snow accumulation and melt processes. These models attempt to trace the fate of incident precipitation to its ultimate fate as stream flow, evaporation, or ground water recharge. Similarly, snowmelt (snow accumulation and melt) models attempt to simulate the history of water storage in a snowpack, including the melt process. Together, these models produce a simulated record of effective precipitation consisting of rain on bare ground and snowmelt, The record is used as input to a soil-moisture accounting model.

Photo credit USDA-Soil **Conservation Service**

Snow surveyors weighing snow sample at Upper Wheeler snow course in Washington State

Simulation models are generally data-intensive and require an experienced user for successful implementation. They have been used for a variety of purposes, of which flood forecasting is one of the most important, However, they have also been used for seasonal runoff forecasting, notably by the California Joint State-Federal River Forecast Center and the National Weather Service (NWS) Hydrologic Research Laboratory.

The advantage for using conceptual models* is that they allow explicit consideration of such factors as soil moisture, which is not usually included in index models. They also allow convenient exploration of alternative scenarios. The Sacramento River Forecast Center, for ex-

* For a discussion of water models in general, see the OTA assessment: *Use of Models for Water Resources Management, Planning, and Policy*. OTA-O-159. August 1982.

ample, was able to provide streamflow forecasts during the 1976-77 drought that were considerably more accurate than those achieved using index methods,

Institutional Responsibilities

Streamflow forecasting has been undertaken seriously for approximately the past 30 years. Responsibilities for runoff forecasting are dispersed among several Federal agencies, and, to some extent, each has developed its own approach to the preparation of a streamflow forecast. Only the NWS of NOAA and USDA's Soil Conservation Service (SCS) are mandated to disseminate forecasts publicly.

In the early 1930's, Congress provided funds and directed the Secretary of Agriculture to initiate a program of snow measurement to be used to estimate the amount of water expected to be available for irrigation use in the coming crop season. This cooperative snow survey and water supply forecast program was first assigned to the Bureau of Agricultural Engineering and later transferred to SCS, where it has remained since approximately 1950 (24).

Beginning in the late 1940's, the U.S. Army Corps of Engineers and NWS jointly undertook another program entitled the "Cooperative Snow Investigations Program, " Its purpose was to initiate an interagency effort to develop the necessary tools for analyzing snowmelt runoff in connection with the respective authorities of the Corps of Engineers and NWS. It included contributions by other agencies, such as the Bureau of Reclamation and the U.S. Geological Survey (USGS) (18), This effort ultimately contributed to the development of the Streamflow Synthesis and Reservoir Regulation (SSARR) model, which is used by the Corps of Engineers and NWS in their joint reservoir-management activities in the Western United States, primarily in the Columbia River basin.

Working independently, in the 1940's NWS (then the Weather Bureau) began to develop short-term forecasting techniques and water supply forecast procedures (1). The Office of Hydrology of NWS began experimenting with continuous streamflow simulation models in 1964, leading to the creation of the NWS River Forecast System (NWSRFS).

Beginning in 1967, SCS initiated the use of a "parametric, deterministic, continuous watershed or basin simulation computer model" primarily to monitor average annual runoff and monthly runoff in several Western States. This model also included an estimation of water requirements of irrigated agriculture,

The National Aeronautics and Space Administration (NASA) in the mid-1970's began a research program designed around the ability of satellites to obtain imagery of various mountain snowpack properties. The primary focus is the area of the ground surface that is snow covered at different times of the accumulation and melt seasons. To date, research has relied heavily on the interpretation of the satellite imagery that relates snow-covered areas in the alpine belt to snowmelt-streamflow from an entire mountain range. Unfortunately, little of the satellite imagery data are readily available to the scientific community at large; thus, no broader use or independent verification is possible. In addition, given the cost of satellite imagery and the data processing required, the costs of this approach currently outweigh its benefits.

Also in the mid-1970's, USGS developed the Hydrometeorological Streamflow Prediction (HM) Method as another forecasting approach. In contrast to the more sophisticated attempts of NASA, this approach uses available low-altitude precipitation and runoff data from existing sites, Its primary advantage is the ease with-which the data are obtainedthe process of forecasting involves a simple accounting method based on precipitation inputs and runoff,

Assessment

Water-supply forecasting for either internal use or public dissemination is an activity in which at least eight Federal agencies and one State agency (California) are now engaged in the Western United States. This has resulted in some competition and confusion, For exampie, until the 1977 forecast season, both SCS and NWS prepared duplicate forecasts for 260 points in the West. In some cases, the forecasts proved to be significantly different, which resulted in some confusion among user groups. In 1978 those agencies entered a cooperative agreement to coordinate their activities and jointly produce and publish "Water Supply Outlooks for the Western United States. "

A primary problem with the conceptual simulation models is the large amount of data required to use them and the relatively long computer running times involved (15). The USGS HM model achieves a balance between data requirements and the desirability of including some representation of physical processes in seasonal forecasts. This model represents forecast season runoff as the difference between total seasonal precipitation falling on the watershed and the sum of winter season runoff and other losses from the system. The seasonal precipitation is determined from measurements at low-elevation precipitation gages in the original HM model. This model has been modified to incorporate snow-course data (15). The relationship between inputs and losses from the system can be expressed also in terms of basin storage, in which forecast season runoff is taken to be winter storage less losses plus forecast precipitation,

The primary advantage of the HM model is that it reflects soil water/runoff interactions in a simple way, which is especially important in extremely dry years, since an accurate forecast is most valuable under extreme conditions, particularly droughts. It has been found that the most accurate runoff forecasts were achieved in extreme high and low runoff years. These are conditions under which the earlier methods perform most poorly, since the relationships used were often linear and most inaccurate when conditions were highly abnormal.

Improvement of runoff forecast accuracy is of practical importance only if it has, some impact on water planning and use. The support of water users for water forecasting programs may be seen as some indication of the worth of the forecasts, For instance, SCS, in considering possible changes to its snow survey and water survey forecasting program, conducted a survey during 1979-80 of users of the program. options included eliminating, continuing, or expanding the program, A large majority of the users supported continuation and/or expansion (15).

Various attempts have been made to evaluate forecast worth. * The most recent of these is the work of Castruccio , et al, (7), which provides estimates of the worth of forecast accuracy improvements throughout 11 of the Western States where snowmelt runoff is the primary source of surface runoff (tables 39 and 40). Five

Table 39.—Summary of the Regional Irrigation Data and Benefits in the 11 Western States[a]

USGS hydrologic region	Benefit ($M)	Benefit/acre (in $/acre)	Percent total impacted irrigated acreage	Estimated average annual crop value/ acre ($/acre)
Missouri	$7.1	$1,14	30.9	$195
Arkansas Red-White	0.9	1,69	2.6	307
Rio-Grande	1.4	3.61	2.0	408
Upper Colorado	1.1	0.86	6.2	184
Lower Colorado	0.8	8.53	0.4	642
Great Basin	2.8	1.56	8.7	209
Pacific Northwest	7.0	1.17	29.5	293
California	5.5	1.39	19.7	592

[a] The 11Western States are Arizona, California, Idaho, Colorado Oregon, Washington, Montana, Wyoming, New Mexico, Utah, and Nevada

SOURCE : P Castruccio, H Loats D Lloyd, and P Newman, Applications Systems Verification and Transfer *Projecf, Volume VII: Cost Benenefit Analysis for the ASVT on Operational Applications o* **Satellite Snow-Cover** *Observations,* National Aeronautics and Space Administration Technical Paper 1828, 1981

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*Currently, there is no direct cost to the users for SCS forecasts, so it is not possible to employ a willingness-to-pay criterion to assess the worth of the information.

Table 40.—Summary of Computed Hydroelectric Energy and Other Relevant Data by USGS Hydrologic Region

USGS hydrologic region	Benefit (v_{IF}) $M	Benefit/MWh ($/MWh)	1978 percent of total hydroelectric energy production (percent)	Current[a] difference between hydroelectric & steamelectric energy production (mills/kWh)	Current[a] difference between 1^{0}& 2° revenues from the sale of energy (mills/kWh)	Streamflow forecast error (percent)
Missouri	1.0	0.17	3.2	7.70	21.43	27.5
Arkansas Red-White	0.05	0.18	0.1	7.73	21.41	29.0
Rio Grande	0.1	1.03	0.1	17.57	19.16	43.8
Upper Colorado	1.1	0.2	3.2	6.50	23.89	24,2
Lower Colorado	2,1	0.46	2.5	18.07	15.33	89.9
Great Basin	0.1	0.24	0.3	19,36	4.36	39.4
Pacific Northwest	3.8	0.03	73,1	7.57	3.63	11.9
California	1.9	0.06	17.7	26.08	6.69	10.0

[a] Values shown have been adjusted for inflationary rises on production expenses (Inflationary factor = 1.21) and sales revenues (inflationary factor = 1.26)

SOURCE P Castruccio, H Loats, and D Lloyd, and P Newman, *Applications Systems Verification and Transfer Project, Volume VII: Cost/Benefit Analysis for the ASVT on Operarational Applicatlons of* **Satellite** *Snow-Cover Observations,* National Aeronautics and Space Administration Technical Paper 1828, 1981

water uses that might be affected by water-supply forecasts have been identified: hydroelectric energy generation, irrigated agriculture, municipal and industrial uses, navigation and recreation, and fish and wildlife (7). Of these, hydroelectric energy generation and irrigated agriculture were identified as being by far the most economically significant. In considering an arbitrarily selected forecast improvement of 6 percent over the existing situation, these authors found a wide range of economic benefits for the individual water subregions of the Western United States. The economic benefit was found to be related to both the accuracy of present forecasts and the value of agricultural products or electrical energy produced by the water. For irrigated agriculture, they projected increased economic values ranging from $0,32 to $12,33 per surface water-irrigated acre. The highest values were found for the Lower Colorado River Basin, where forecast accuracy is low and the value of crops produced by irrigated agriculture is high. The lowest values came from the Pacific Northwest, where forecast accuracy is relatively good. The economic benefit for hydroelectric energy generation was calculated to range from $0.03 to $1.03 per million watt-hour (MWh). They calculated that the annual economic benefit for the 11 Western States resulting from a 6-percent increase in forecast accuracy for irrigated agriculture would be $26,476,739 and for hydroelectric energy generation, *$10,032,798.* These benefits are summarized in tables 39 and 40.

Improvement of streamflow forecast accuracy, in general, is dependent on a number of factors, including forecast technology, watershed characteristics, climatic conditions, and data availability and reliability, In some cases, where adequate data are available and existing forecast methods are based on the development of a simple statistical relationship between some variable, such as snow water-equivalent depth, and annual runoff volumes, it may be possible to achieve forecast improvements of at least 25 percent over existing methods (15). More commonly, improvements in the range of 10 percent appear to be a more reasonable estimate. As noted above, even this modest improvement has the potential for producing a considerable economic benefit by improving the management efficiency of the reservoir system of the Western United States.

Water-supply forecasting would benefit from an increased understanding of the highland watershed environment, It would also benefit from increased coordination and cooperation among the various Federal and State agencies involved, primarily to eliminate any areas of duplication. Primary research efforts could be directed toward improving the ability to forecast the timing of the annual spring runoff. Forecasts of annual volume are reasonably accurate for most of the forecast techniques, although some effort could be expended in obtaining small increases in this accuracy. It has been suggested that even small increases in the forecasts of streamflow volume for certain regions in the Western United States would have considerable economic benefit for agriculture,

CONCLUSIONS

Three major categories of technologies (weather modification, watershed management, and streamflow forecasting) have evolved to estimate and manipulate the surface runoff produced annually or seasonally by precipitation on watersheds in the Western United States. Debate and uncertainty exist in each of these categories regarding their effectiveness and potential.

The two weather-modification technologies that have received the most attention are those involving: 1) winter storms that cross the major mountain ranges of the Western United States, producing the snowpack of the mountain watersheds, and 2) the summer cumulus clouds that produce rain and hail, often in large amounts over limited areas. While “seeding” these air masses could produce additional precipitation under the right conditions, more research is needed on whether this reaction results in increased soil water or surface runoff in the target area, Additional information is also needed on the physical interaction between the artificial nucleating agent and the existing physical properties of an air mass and on the development of acceptable verification criteria for evaluating the success of a cloud-seeding experiment.

Watershed-management technologies are designed to manipulate the water resource once precipitation has reached the ground for onsite or offsite use, In the Western United States, the most important of these technologies from the standpoint of volumes of water are those intended to increase surface runoff from the highland mountain snowpack.

The most water productive of all the major biophysical environments of the region is the alpine zone, that zone in the highest elevations of the major mountain ranges, This zone has received little scientific attention, The few alpine studies suggest that a conservative, passive-management approach may be the most beneficial technology for the present.

Technologies that affect the montane zone have involved, to a great extent, the removal of all or portions of the mountain forest in an attempt to alter snow-accumulation patterns, evapotranspiration losses, or rates of meltwater production. It has not yet been established that forest removal will result in predictable runoff increases for downstream arid/semiarid agriculture.

Attempts to modify the surface runoff regime in lowland watersheds involve a wide range of technologies, depending on the specific environment involved and possible objectives. In some cases, the production of increased runoff is desired; in others, the retention of water for onsite uses is the goal. Generally, the approach is to modify vegetation or the physical surface area of the site. Results in these regions have been variable because of the different objectives and because of natural variations in lowland watersheds.

Water-supply forecasts are undertaken by several Federal and some State agencies to improve regulation of reservoirs that control the surface flow of Western rivers. These efforts sometimes are not coordinated and include aspects of duplication and inconsistency. A wide range of forecast models exists, from very sophisticated, computed simulation technology to simpler statistical correlation models, Research has indicated that no single forecast model is sufficient for all hydrometeorological environments in the West. In general, those models having the simplest data and computer processing requirements would appear to be most desirable, strictly from local use, economic, and efficiency standpoints, An example of this type of model is USGS’s HM model. Attempts are being made also to incorporate satellite imagery and data acquisition by remote telemetry into the data input required for forecasting. Much improvement is possible in forecasting techniques to assist in more effective water-resources planning and management for all Western users, including the major user, agriculture.

Each technology assessed in this chapter has demonstrated that it can, at least on a local, site-specific basis, either augment runoff from mountain watersheds or forecast the volume of that runoff. In every case, however, it has proven difficult to demonstrate that the results can be generalized over extensive areas. Of the technologies to augment runoff, precipitation augmentation from winter orographic storm systems by “cloud seeding” appears to show the most potential, This technology, while not living up to some of the claims of its more enthusiastic supporters, has been developed within a solid scientific framework that has created a body of knowledge that should facilitate future studies. Watershed management, on the other hand, has been approached largely as an adjunct of commercial logging operations. For this reason, the relationship between deforestation or afforestation and water yield from highland watersheds is much more speculative. This entire subject area would benefit from a more rigorous scientific approach emphasizing water yields rather than timber production if it is to be given serious consideration as a technology capable of producing additional water for Western agriculture. Technologies for the management of lowland watersheds to increase water yield can be applied locally (e.g., to produce water for stock ponds), but in general they cannot create sufficient additional runoff to affect regional supplies, except in exceptional circumstances.

Water-supply forecasting is gradually developing approaches based on more realistic models and more sophisticated data collection techniques. Water-supply forecasting technologies should form the foundation of water management and planning in the Western United States. As such, responsible Federal agencies should be encouraged to evaluate critically the existing forecast systems, to develop a more detailed study of the processes controlling snow accumulation, melt, and runoff from highland watersheds; and to coordinate their efforts with those involved in precipitation augmentation and watershed-management technologies,

Finally, a more coordinated approach to the study and management of highland hydrologic systems would greatly benefit each of the technologies discussed in this chapter. Ideally, the goal of this effort would be the development of an ability to trace the path and history of water from the time it originates as augmented precipitation in a winter orographic storm through deposition, melt and ultimate runoff into either the rivers or reservoirs of the region, and evapotranspiration or percolation to ground water.

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