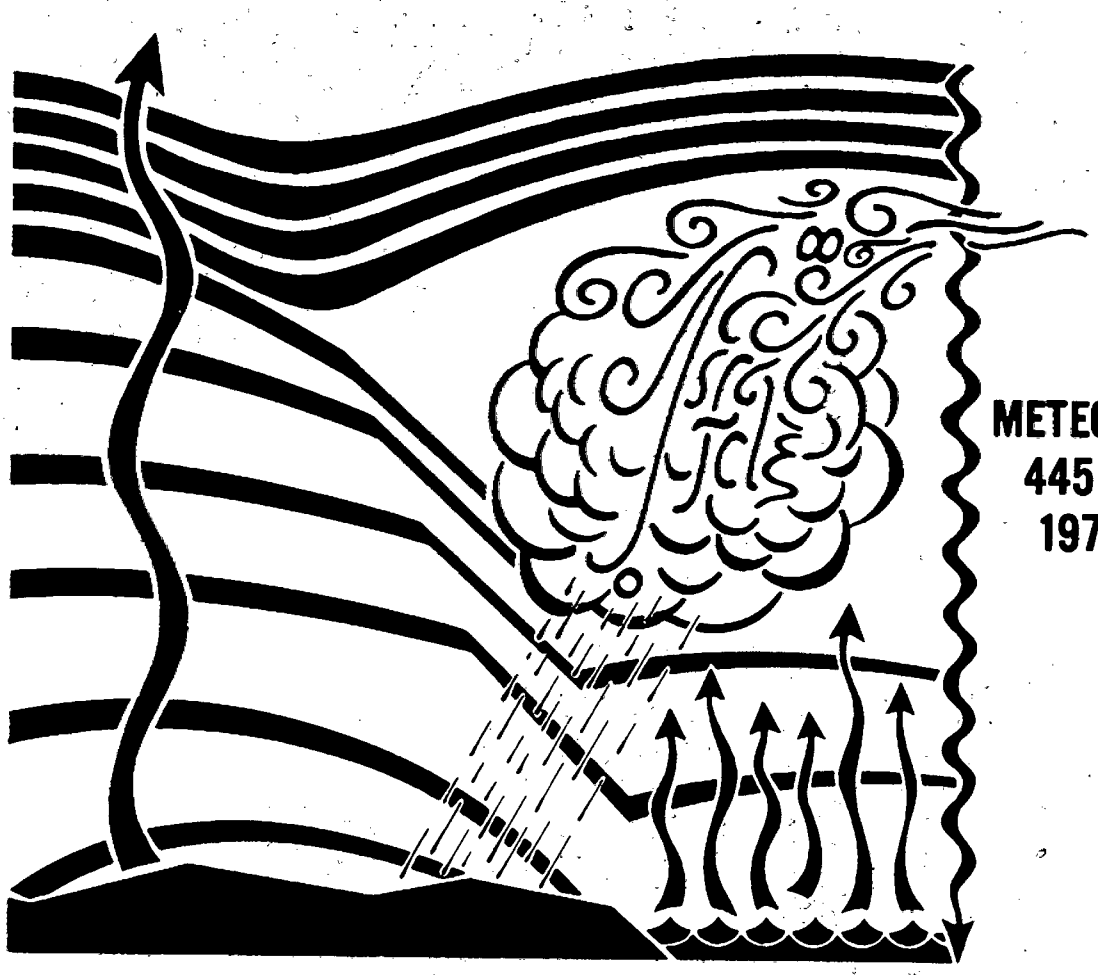
PENN STATE

POSSIBLE EFFECTS OF WEATHER MODIFICATION ON THE HYDROLOGIC CYCLE



by
METEOROLOGY
445 CLASS
1970-1971

DEPARTMENT OF METEOROLOGY THE PENNSYLVANIA STATE UNIVERSITY

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POSSIBLE EFFECTS OF WEATHER MODIFICATION ON THE HYDROLOGIC CYCLE

Prepared by the
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ABSTRACT

"Possible Effects of Weather Modification on the Hydrologic Cycle" is a report written for the U. S. Bureau of Reclamation by Penn State students. The report focuses on how individual parts of the hydrologic cycle could be influenced by a hypothetical 10% increase in annual precipitation over the Upper Colorado River Basin. Specific topics considered are: physical features, evapotranspiration, soil moisture and groundwater, streamflow, and social, economic, and legal factors. Suggestions and conclusions are included in the study.

ACKNOWLEDGMENTS

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PREFACE

In recent years considerable attention has been given to the study of weather modification. In addition to the study of this subject, time, money, and effort must be focused on the effects modification may have on the total environment. The following report is designed to indicate what hydrologic cycle changes might occur in the Upper Colorado River Basin as a result of weather modification. The report also includes an investigation of the potential social, economic, and legal ramifications of changes in the hydrologic cycle caused by weather modification.

The study was conducted by a group of meteorology students at The Pennsylvania State University as a term project in Meteorology 445, Hydrology for Meteorologists. The paper was written for the Bureau of Reclamation, Department of the Interior, with their specific interests in mind. The subject of the seven-week study was divided into five categories. Each category was handled by an individual class group and coordinators were used to channel the efforts of the groups into a preliminary final report, which was later edited by a smaller group of the students.

The relatively short time devoted to the study limited the depth of the report, eliminated the possibility of field research, and made it necessary to obtain basic information from other sources. The report, however, does consolidate important information and attempts to draw conclusions about the effects of weather modification on the hydrologic cycle of the Upper Colorado River Basin. The report is largely qualitative and hopefully provides a basic foundation upon which further research can be done.

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INTRODUCTION

The hydrologic cycle is composed of numerous components and the interactions between these components are quite complex. Each time a perturbation is introduced, such as an intense rain or early snow, the entire hydrologic cycle reacts. The purpose of this report is to determine how the various components of the hydrologic cycle will react to an increase in annual precipitation. The principle components of the hydrologic cycle discussed are evapotranspiration, soil moisture and groundwater, and streamflow.

The manner in which the hydrologic cycle transports water depends upon the physical features and climate of an area. It is important to discuss these features and determine how hydrologic cycle processes are dependent upon them. Finally, any reactions within the hydrologic cycle to varying climatic changes can be qualitatively assessed. The following study is done in this manner.

The study limits the research area to the Upper Colorado River Basin because 1) the areal scale is of workable dimensions, 2) there have been numerous research projects conducted there on the subject. Initially, the important physical features and climate of the research area are established. The study then treats each component of the hydrologic cycle separately and discusses the reaction of each to a 10% increase in annual precipitation. The final section of the report discusses the economic, social, and legal problems arising from changes in the hydrologic cycle as a result of weather modification.

Most of the conclusions in the report regarding how the various parameters of the hydrologic cycle will react to an increase in precipitation are qualitative. However, the assumption that annual precipitation is increased by 10% was made in order that some quantitative conclusions could also be drawn. Additional assumptions are discussed in the section to which they pertain.

CHAPTER I.

PHYSICAL FEATURES

A. General Location of the Colorado River Basin

The Upper Colorado River Basin covers approximately 109,500 square miles in parts of five states: western Colorado, southwestern Wyoming, eastern Utah, northwestern New Mexico, and northwestern Arizona (Figure 1). The Basin is part of two large physical divisions of the United States--the Rocky Mountains and the Intermontane Plateau. The terrain in the Basin varies from rugged snow-covered mountains to dry lowland regions. Melting winter snows and summer thundershowers feed the streams of the three major divisions of the Basin: the Green, Grand, and San Juan (Figure 2).

B. Topography and Structure

1. General Topography

The Upper Colorado River Basin is a mountainous plateau, 5000 to 8000 feet in elevation, marked by broad rolling valleys, deep canyons, and intersecting mountain ranges. Hundreds of peaks in these mountain chains rise to more than 13,000 feet above sea level. Figure 3 presents a general view of the topography in the Basin.

The Green Division stretches from the sources of the Green River in the north at an elevation of nearly 14,000 feet, to the junction of the Green and Colorado Rivers far to the south at an elevation of 3880 feet. The Division is bounded by a series of mountain ranges and plateaus scattered on its perimeter. It is also divided from west to east by the Uinta Mountains which merge into foothills in the east. Many lakes can be found in the mountains, forming the beginning of most of the principal streams of the area. In contrast to its rugged boundaries, the Green Division has broad valleys in much of its interior.

The Grand Division is bounded by plateaus to the west and north and by mountain ranges to the east and

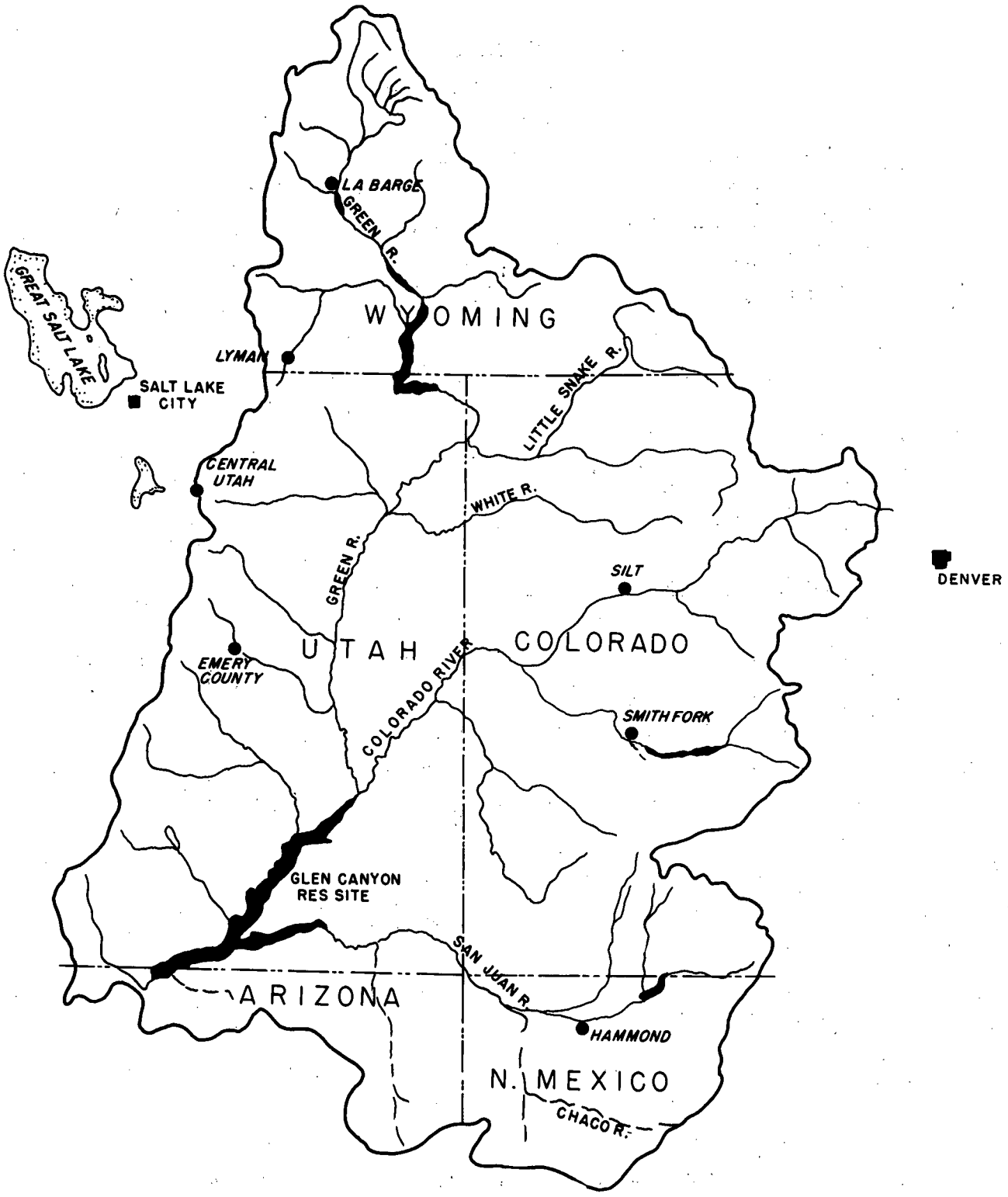

Figure 1
The Upper Colorado River Basin
(Rasmussen, 1968)

Figure 2
Sub-Divisions of the Upper Colorado River Basin
(Rasmussen, 1968)

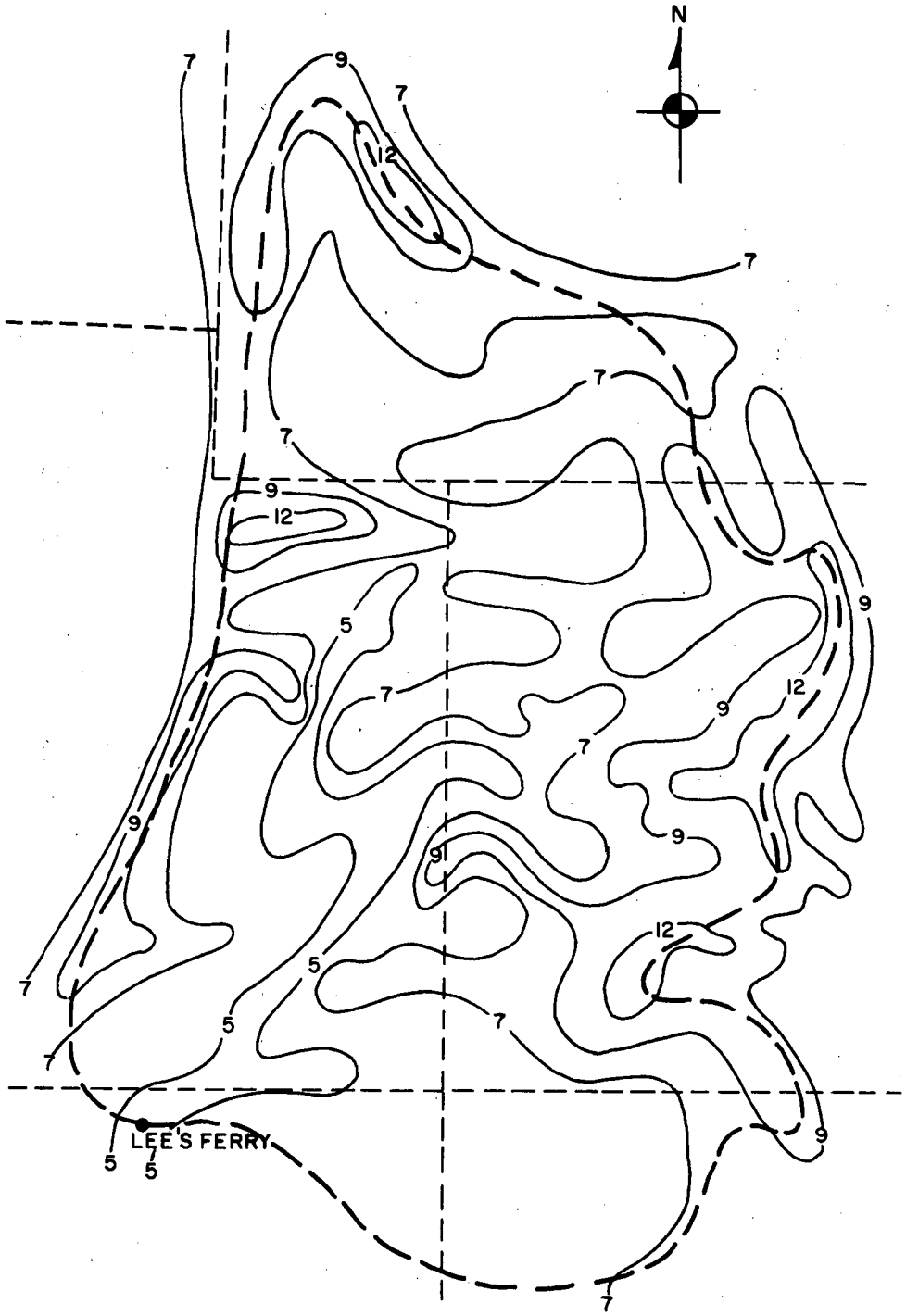

Figure 3
Elevation Map
(in 1000's of feet)
(Rasmussen, 1968)

TABLE A

AREAL COVERAGE OF PRECIPITATION IN THE UPPER COLORADO RIVER BASIN

Precipitation Range	GRAND DIVISION		GREEN DIVISION		SAN JUAN DIVISION		ENTIRE UPPER COLORADO SUB BASIN	
	Area in Sq. Mi.	% of Sub-division	Area in Sq. Mi.	% of Sub-division	Area in Sq. Mi.	% of Sub-division	Area in Sq. Mi.	% of Entire Upper Basin
60-70	0	0%	15	.033%	31	.08%	46	.042%
50-60	32	.12%	129	.29%	213	.56%	374	.34%
40-50	606	2.28%	582	1.31%	627	1.66%	1,815	1.65%
30-40	3,362	12.69%	3,006	6.7%	903	2.36%	7,271	6.64%
25-30	3,304	12.47%	2,857	6.40%	745	1.95%	6,906	6.3%
20-25	4,178	15.76%	3,761	8.42%	1,132	2.96%	9,071	8.27%
16-20	4,971	18.76%	5,711	12.78%	3,229	8.44%	13,911	12.7%
12-16	5,414	20.44%	11,112	24.86%	7,108	18.55%	23,634	21.57%
10-12	1,983	7.48%	6,499	14.54%	6,719	17.54%	15,201	13.87%
8-10	1,592	6.0%	5,796	12.97%	8,029	20.96%	15,417	14.07%
6- 8	1,058	4.0%	5,051	11.29%	8,017	20.93%	14,126	12.9%
4- 6	0	0%	181	.40%	1,547	4.03%	1,728	1.57%

Source Reference: Iorns, et al., 1965

southeast. The eastern part of the Division is a series of uplifted mountain masses dissected by streams in deep canyons and U-shaped valleys. The only flatlands in the east are narrow flood plains and terraces along the main streams.

The western part of the Grand Division is essentially a dissected plateau and the relief is not as great as in the east. Streams flow through wide valleys bordered by large areas of relatively flat land.

The San Juan Division is bounded by mountain ranges and plateaus to the northwest and northeast. Much of the southern half of the Division is a flat, arid region. Thus the San Juan Division possesses great contrasts in topography: "parched deserts and lush mountain meadows; high mountains, deep canyons, and broad valleys; dry stream channels and rushing mountain torrents." (Iorns, et al., 1965)

2. Soils

Four types of soil are found in the Upper Colorado Basin: alluvial, residual, glacial, and aeolian.

Alluvial soil is comprised of stream-deposited materials. It is common throughout the Basin but is confined to the flood plains and adjacent terraces along the streams. Alluvial soil varies widely in depth and maturity. Its composition and texture are dependent upon: (Iorns, et al., 1965)

1. the age of the material
2. the distance and mode of transportation
3. the type of rocks from which it was derived.

Residual soil is the most common type found in the Basin. It consists of products of rock weathering that have accumulated faster than they can be removed by water and wind. It ranges widely in thickness and quality throughout the Basin; where temperature and moisture characteristics are favorable, residual soil is deep and mature; in drier parts of the Basin, it is shallow and poorly developed.

Glacial and aeolian soils are not as common as alluvial and residual. Glacial soils appear in the form of glacial deposits or out-wash plains derived partly from granites or other igneous materials of the higher mountains. It can be found scattered throughout the Basin.

Aeolian, or wind-blown soils, are not extensive. Some are found in small areas south of the San Juan River along the northeastern sides of ridges or along other uplifts that break the winds and trap the materials.

C. Climate and Precipitation

Generally, the Upper Colorado River Basin has a climate of extremes. Regions with high annual precipitation are usually those areas where orographic lifting of moisture-laden air masses occurs. Annual precipitation in the southern portion of this Basin is generally quite low, typical of the climatology at these latitudes. As would be expected in mountainous regions, upslope and downslope airflow are largely responsible for the climatic patterns of this Basin. Each of the subbasins, the Green, the Grand, and the San Juan, vary in their climatic characteristics and merit individual discussion.

Table A illustrates the distribution of liquid precipitation, in inches, over the entire Upper Colorado River Basin and over its component divisions. The two columns under each division contain first, the area in square miles of the division upon which a certain amount of precipitation falls; and second, the percentage of the division this square mile area represents.

The last two columns of the table contain the square mile area of the entire Upper Colorado River Basin where a certain amount of precipitation falls and the percentage of the total Basin this area represents.

1. The Green Division

The climate of the Green Division ranges from extremes of high precipitation and cold temperatures in the

mountains to scant precipitation and high summer temperatures in the interior basins.

The mountains along the western side act as partial barriers to incoming Pacific air masses that cross the Division. The Uinta Mountains retard the movement of air-masses in the north-south direction. The area north of the Uinta Mountains is affected by cold polar air masses while, south of the mountains, warm, moist air masses from either the Gulf of Mexico or the Pacific trigger the precipitation.

During the winter months, from October to April, the majority of the precipitation, especially in the high mountains, is in the form of snow. North of the Uinta Mountains, the average seasonal precipitation varies very little. To the south, however, the area has varying seasonal precipitation patterns. During the summer months, because of the strong influx of moisture into the south, the area to the south of the Uintas experiences intense showers and thundershowers.

2. The Grand Division

Mountain ranges enclose the Grand Basin on three sides and serve as barriers to approaching air masses. The mountains trigger precipitation through air mass lifting and thus the climate within the basin is naturally modified. Air masses that move across the Division from either the north or east characteristically precipitate due to upslope motion. The rain or snow from these systems is deposited on the plateau. During the summer and early fall months, storms feeding on moisture available in the Gulf of Mexico spread their precipitation shields to the north and west. These storms occasionally produce flash flooding. Along the western portion of the southern boundary the mountains are not high enough to retard air mass movement from the Gulf of Mexico; the result is intense summer storms, occasionally strong enough to produce flash flooding. The western portion of the Grand Basin, however, is more directly exposed to Pacific air masses, and ultimately,

from October to April, these air masses drop their snow in the high mountains where it accumulates to great depths.

3. The San Juan Division

The climate of the San Juan Division ranges from extremes of high precipitation (60"-70"/yr.) and low temperatures (26°F) in the San Juan Mountains to scant precipitation (4"-6"/yr.) and high summer temperatures (73°F) at the lower elevations (Iorns, et al., 1965). The major part of the Basin is less than 6,000 feet above sea level and receives less than 8 inches of precipitation per year.

The air masses that affect this Basin usually have their origin in either the Gulf of Mexico or in the Pacific. The uplands along the southern boundary are lower than those along the northern boundary; consequently, air masses easily move from the south across the basin. Abundant precipitation is found in the eastern part of the Basin where the moisture laden air masses from the Gulf are orographically lifted along the San Juan Mountains.

Snow at the higher elevations is the principal source of water supply for the Division. In contrast to the Grand and Green Divisions, the San Juan Division has more precipitation during the summer than during the other seasons.

D. Vegetation

Vegetation in the Upper Colorado River Basin has changed very little since the area was settled. Only a small part of the Basin is cultivated and those trees that are cut for lumbering are replaced by means of reforestation and range improvement programs. The variety of vegetation indicates the many different climatic conditions present in the area. There are great differences in rainfall, temperature, topography, and soil type which have lead to sharp contrasts in vegetation type over relatively small areas. The twelve important plant communities in the area are the alpine meadows, subalpine forests, montane forests,

mountain brush, pinyon-juniper, big sagebush, shadscale, blackbrush, greasewood, saltbrush, summer-cypress, and grasslands.

1. Alpine Meadows

The alpine meadows are above the timberline at usually more than 12,000 feet. The plants usually found here are sedges, bluegrass, spike trisetum, alpine timothy, willows, bistort, bluebells, gentian, and clovers.

2. Subalpine Forests

The subalpine forest is divided into upper and lower subregions. The upper subalpine forest is dominated by Engleman Spruce and subalpine fir trees. In the lower region, dominant species are lodgepole pine, Douglas fir, and quaking aspen. Some areas of the subalpine forest have little or no underbrush because of dense stands of trees. However, where underbrush does exist the plant types include pinegrass, elk sedge, arnica, and huckleberry.

In meadows and along streambanks in the subalpine, forest woody plants such as willows, cottonwoods, aspen, birches, and dogwood are present. Important herbaceous species include tufted hair-grass, bluejoint, sedges, and rushes.

3. Montane Forest

In the montane forests there are large, open stands of Ponderosa pine, usually found growing with assorted types of undergrowth but consisting mainly of mountain muhly, Arizona fescue, Idaho fescue, slender wheatgrass, and oatgrasses. Common shrubs include big sagebrush, service-berry, snowberries, mountain-mahogany, and bitterbush.

Important woody plants along streambanks and in meadows of the montane forest are willows, cottonwoods, aspen, birches, and dogwood. Prominant herbaceous species include tufted hair-grass, bluejoint, sedges, and rushes.

4. Mountain Brush

At lower altitudes are the mountain brush regions which often are transition zones between coniferous forests

and other types of vegetation. Shrubs common to this region are scrub oaks, mountain-mahogany, serviceberry, snowbrush, bitterbrush, cliffrose, chokecherry, snowberry, and rose. Other plants found in the area included big sagebrush, bluebunch, wheatgrass, needle-and-thread, junegrass, and annual bromes.

5. Pinyon Juniper

The pinyon-juniper zone is in low mountain areas, usually between 4000-6000'. The most common junipers are the juniper, Rocky Mountain juniper, and one-seed juniper. Colorado pinyon is the most common pine and has an undergrowth consisting of bitterbrush, big sagebrush, mountain-mahogany, and cliffrose. Herbaceous species include blue gramma, galleta, bluebunch wheatgrass, Indian rice-grass, Russian thistle, and cheatgrass.

6. Big Sagebrush

Big sagebrush is not entirely restricted by altitude and occurs in wide areas up to 10,000', usually on well-drained, non-saline, sandy soils. Some shrubs associated with sagebrush are rabbitbrush, horsebrush, winterfat, and snakeweed. Undergrowth grasses are galleta, bluegramma, western wheatgrass, bluebunch wheatgrass, and squirreltail.

7. Shadscale

Shadscale is limited to slightly saline, impermeable soils and occasionally grows in pure stands; however, it is often associated with other shrubs such as sagebrush, horsebrush, and spiny hopsage.

8. Blackbrush

The blackbrush zone is characterized by sandy, non-alkaline soils at lower altitudes. Plants in this zone include fourwing saltbush, Mormon tea, yucca, snakeweed, and galleta.

9. Greasewood

Greasewood grows above permanent streams. This type of plant community is salt-tolerant, deep-rooted, and

is usually indicative of the presence of ground water. It often grows in pure stands, but is sometimes associated with shadscale, sagebrush, and rabbitbrush.

10. Saltbush

Saltbush grows in salty, heavily textured soil of minimal permeability. Greasewood and sagebrush often grow with saltbush in small channel bottoms. Winterfat and blacksage are also commonly found in the saltbush community.

11. Summer Cypress

Summer cypress is scattered in the northern part of the Division at low altitudes and on heavy, dry, saline soils. Plants often found growing with summer-cypress are bud sage, winterfat, sandberg bluegrass, Indian ricegrass, and scarlet globemallow.

12. Grasslands

Grasslands, and grasslands with shrubs, are extensive. Grasslands in the higher altitudes are scattered and include western wheatgrass, bluebunch, wheatgrass, squirreltail, and needlegrass. The most common grasses in the lower altitudes are bluegramma and galleta.

CHAPTER II.
EVAPOTRANSPIRATION

A. Introduction

Before increasing the precipitation of an area it is necessary to evaluate the effect this modification would have on the evapotranspiration. It is also important to obtain at least a general understanding of how the environment would be affected by a change in the evapotranspiration rates. For best results, weather should be modified during seasons when conservative increases in precipitation would enhance plant growth, with the excess water contributing to streamflow, groundwater, or the soil moisture reservoir.

It has been assumed prior to this discussion that a 10% increase in annual precipitation can be obtained in the Upper Colorado River Basin. Climatological studies suggest that this is a reasonable figure as a result of fall and winter weather modification in this region. In this section, fall and winter evapotranspiration will be the primary concern.

B. Transpiration and Interception Losses

In order to assess transpiration losses in any vegetative regime, the following factors must usually be considered:

1. Vegetation species and their distribution
2. Vegetation size and maturity
3. Season
4. Length of transpiring day

Studies by Swanson (1967) and Richard (1967) verified the importance of the vegetation species on transpiration loss. The vegetation of the Upper Colorado varies from conifers, predominant in the mountainous regions, to the vegetation of the lower altitudes, where deciduous forests and a variety of shrubs and bushes are the major moisture consumers. The transpiration rates of conifers during the

late fall and winter have been estimated at .024 grams water per 100 cm^2 per hour (Kozlowski, 1943). As conifer density increases, so does the total transpiration loss. For hardwood trees and shrubs, transpiration losses during the fall and winter months can be neglected because many of these plants are leafless.

One further factor in transpiration loss is the length of the transpiring day. This varies with the season and vegetation species, as well as the soil mositure availability and air temperature.

During the fall and winter, when precipitation is largely snow, it might be expected that interception would cause reduced transpiration. The possible reasons for this reduction would be the result of:

1. The finite amount of energy available for evaporation at any one time. This evaporation would either be from within the leaf or from the leaf surface.
2. Transpiration reduction because of plant surface wetting.
3. Vapor pressure gradients directed towards the interior of the leaf surface because of greater atmosphere moisture content.
4. Lower leaf temperatures because of increased solar reflection.

Interception losses during this season for conifers are generally small (5-14%) (Rango, 1970) and losses from deciduous trees are negligible. Considering the ease with which snow can blow off or fall through conifers and deciduous trees, these figures seem reasonable. Consequently, because forest interception is small, transpiration can continue relatively unrestricted. Large areas of the Colorado River Basin, however, are covered with mature grasslands and shrubs rather than forests. In the winter interception losses from shrubs and grasslands and those

losses found within the forest are nearly equal. Consequently, the combined effect of deciduous and coniferous trees, grasses, and shrubs has minimal effects on interception loss. A value of 5-14% for winter interception losses from both forested and unforested areas seems to be a reasonable figure.

At best, any quantitative measures of transpiration or interception losses for the Upper Colorado would be a rough estimate. The Basin is too large to render exact accounts of either of these processes. In addition, exact measurements of transpiration and interception have not been made for all species of vegetation. The observations that have been presented suggest, however, that modification in the fall and winter will allow transpiration processes to resupply the atmosphere with moisture without being substantially retarded by interception loss by the vegetation.

C. Vegetation Growth Due To an Increase in Precipitation

Plants function and grow according to the supply of water available for transpiration uses. Vegetation types native to deciduous forests of the Upper Colorado River Basin are capable of transpiring 40 inches of water per growing season at maximum levels when abundant water is available. Normal transpiration levels, however, of both deciduous and coniferous vegetation of the Basin are lower because of soil moisture deficiencies. The amount of water transpired by plants varies from year to year, but probably does not exceed 25 to 30% of the total rainfall. The majority of this water is used by plants to transport nutrients which enable the plant to grow.

Vegetation does not grow at the same rate throughout the year. During the winter, transpiration rates are quite low. In this discussion, deciduous trees are assumed to be dormant during the winter. Transpiration losses by conifers in the winter should remain constant if average wintertime precipitation amounts are sufficient to meet the intake requirements of the vegetation. Vegetation depletes

very little moisture from the soil during these months. The melting of snow more than compensates for the transpiration losses by recharging the soil moisture reservoir. As spring arrives, warmer temperatures cause an end to dormancy and the vegetation begins to grow. The abundance of water in the nearly saturated winter soil reservoir allows plants to carry on growth processes at a maximum rate. This period of rapid growth continues until levels of soil moisture decrease with the approach of summer and the dry season.

If weather modification could increase the precipitation, and in turn, the water availability for plant use, vegetation would be influenced. If a 10% increase in winter precipitation could be applied to the snowpack, a greater storage facility for water could be created. With typical spring temperatures initiating the snowmelt process, and with a greater depth of snow, the snowmelt season would be extended; this is of great importance to the growing season. If rain was increased during the early spring, a great deal of the precipitation would run off the saturated soil. Rain in late spring would be effective in replenishing reduced soil moisture levels. As the peak growing season ends, and the dry weather associated with summer approaches, precipitation increases have little effect. A level of two inches of rain per week, an abnormal value for the summer months in the Basin, would be necessary to maintain a saturated soil. In conclusion, the most beneficial time of year for a 10% precipitation increase would be during the fall and winter. This appears to be the time when snows and the resulting apringtime snowmelt can effectively recharge the soil moisture reservoir and ultimately enhance vegetation growth.

D. Computer Program For Estimating Potential Evapotranspiration

In order to estimate how a change in precipitation amounts would affect the potential evapotranspiration of the

Upper Colorado River Basin, a first estimate of the present potential evapotranspiration must be made. In doing so, an empirical formula which best suits the area was selected. The research area was divided into three relatively homogeneous sections on the basis of annual precipitation and the parameters related to the formula. Using this formula, an estimate of the average potential evapotranspiration in each area was determined. If an estimate can be made of how the parameters are affected by a precipitation change, an estimate can also be made of the potential evapotranspiration change for each area.

Cruff and Thompson (1967) presented a comparison of six commonly used methods for estimating potential evapotranspiration from climatological data. The methods tested were: Thronthwaite, U. S. Weather Bureau (modification of the Penman method), Lowry-Johnson, Blaney-Criddle, Lane, and Hamon. To test the applicability of each of these methods in arid and sub-humid regions, they chose 25 test sites in Arizona, California, and Nevada. The average annual rainfall at these sites compared favorably with the average annual rainfall in the Upper Colorado River Basin.

The methods of Blaney-Criddle and the U. S. Weather Bureau were the only techniques which gave satisfactory results over the entire region tested. The Weather Bureau method was used at only seven sites because of climatological data limitations in the region; however, where it was used, the results were promising. The Blaney-Criddle method includes a crop coefficient. As a result, this method is difficult to apply in the Upper Colorado River Basin because no crop coefficients have been derived for natural vegetation. Because of this the Weather Bureau method was selected as the better of the two.

The Weather Bureau method, developed by Kohler, Nordenson, and Fox (1955), is a modification of the formula

developed by Penman (1948). Lake evaporation, which is considered to be a good estimation of potential evapotranspiration, is related to air temperature, dew point, wind speed, and solar radiation. Lamoureux (1962) adapted this method for computer use. Consequently, a FORTRAN program, using this adaption, has been used (see Appendix). The following results were obtained:

Figure 4 shows how the research area was divided according to the various characteristics of the area. For example, Area 1 is relatively cold and wet with an average annual temperature of 41°F and an average annual precipitation of 20 inches. The elevation of the stations in this sector range from 6500 to 9300 feet above sea level. On the other hand, Area 3 is relatively warm and dry and has an average annual temperature of 51°F and an average annual precipitation of 8 inches. Station elevations for Area 3 are considerably different than Area 1 ranging between 4300 and 5500 feet. Area 2, with an average annual temperature of 48°F, an ayerage annual precipitation of 12 inches, and elevations between 5500 and 6500 feet, is an area selected as a "middle ground" between Areas 1 and 3.

The estimated yearly totals for potential evapotranspiration in Areas 1, 2, and 3 were 55.4, 67.4, and 72.6 inches respectively; however, these results appear to be quite high (see tables D, E, and F in Appendix). According to a national map of lake evaporation, values for the entire research area should range between 30 and 40 inches per annum. Accordingly, a coefficient of .56 was used to modify the calculated potential evapotranspiration values. Since the .56 coefficient seemed to reflect a large percentage error in the initial findings, a program error was suspected; Cruff and Thompson (1967), using the Weather Bureau Method, obtained excellent results in areas of somewhat similar climatic conditions. The program was checked by using two sites that Cruff and Thompson used:

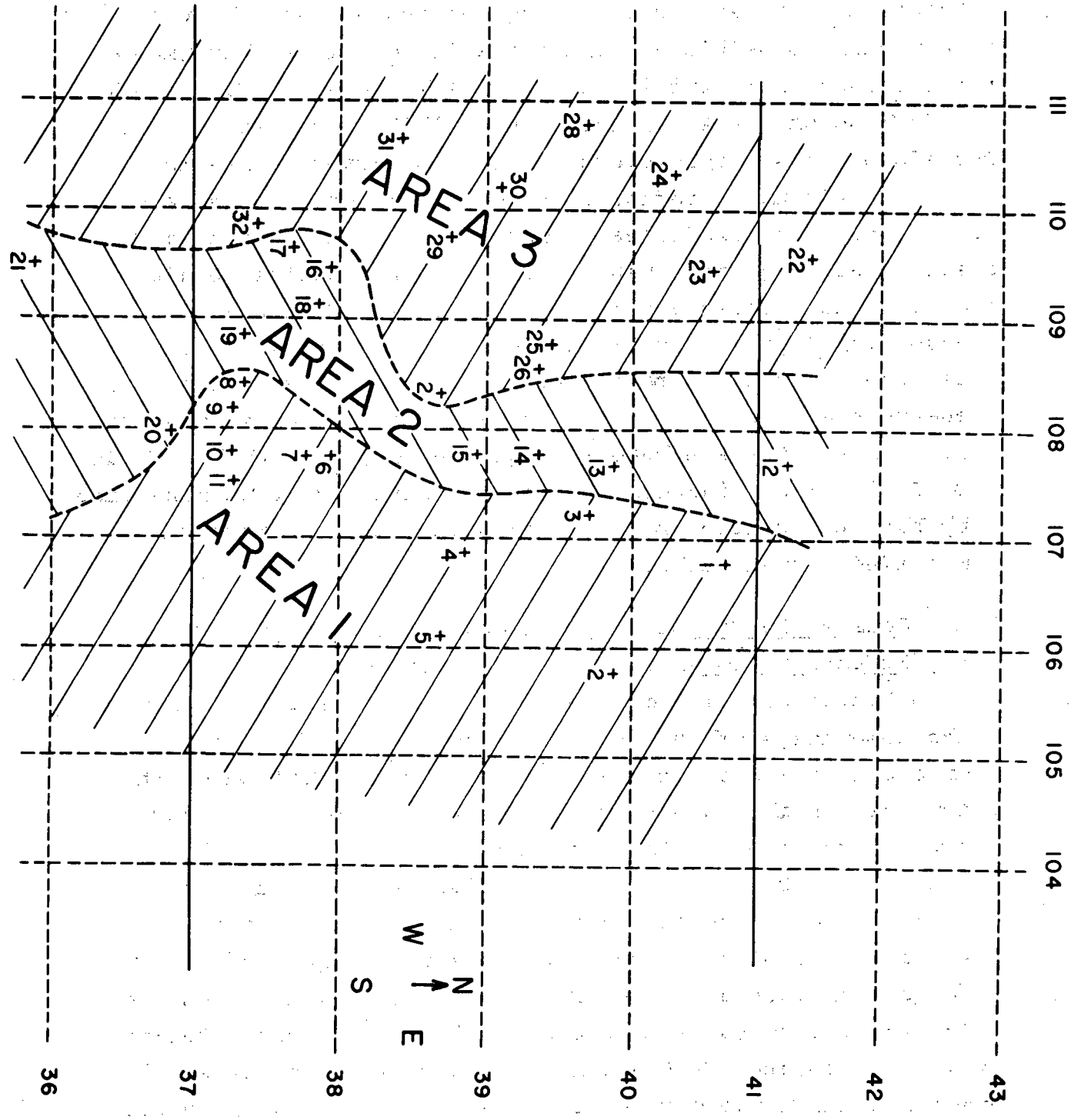

Figure 4

Computer Division of the Research Area (numbers refer to climatic stations used in the study)

Los Angeles and Las Vegas. Using the Cruff and Thompson values where possible and interpolating values where needed, the results fell within 4% of the values obtained by Cruff and Thompson for Los Angeles and within 1% for Las Vegas. Therefore, it was concluded that no program error existed.

The primary difference between this group's research area and that of Cruff and Thompson is that average wind speeds are higher and the research areas were higher in elevations. The Penman method was modified with an advection term for use in arid and semi-arid climates because it underestimated evaporation due to advected energy. Accordingly, it could be that this advection term overcompensates when the average wind speed is high. Tables D, E, and F found in the Appendix indicate results generated by both the Weather Bureau procedure and this group's modified Penman method.

E. Changes In Various Climatic Parameters and Their Effects On Potential Evapotranspiration

Little quantitative information is available on how the components of the hydrologic cycle are affected by precipitation amounts. With careful consideration of the few details that are known, the modified Weather Bureau method presented in this report makes estimates of how evapotranspiration rates would be affected by weather modification. In particular, estimates of potential evapotranspiration and its response to changes in temperature, dew point, and solar radiation have been made for Area 2, a region most climatologically representative of the Upper Colorado River Basin. Because increased precipitation usually results in both lowered temperatures and solar radiation values, but increased dewpoint temperatures, the resultant effects of these changes on evapotranspiration are revealed in Table B. The new program, a variation of the Weather Bureau's program using

a coefficient of .56, has generated the results (see program in Appendix).

Column 1 of Table B gives the normal monthly evapotranspiration rates with average yearly temperature 47.7°F, dew point 25°F, and solar radiation 500 ly/day (U. S. Environmental Data Service, 1968). Column 2 estimates the evapotranspiration rate which would accompany a temperature drop of 1°F, a dew point rise of 2°F, and a solar radiation reduction of 15 langleys per day. These changes are characteristic of a 10% precipitation increase. Column 3 represents the parametric changes with a 10% decrease in precipitation. Columns 4 through 11 are estimates of evapotranspiration rates with greater deviations from the norm in both temperature and dew point. Precipitation changes of much more than 10% are required to alter these quantities to such an extent.

Variables Used in the Table

T - air temperature in degrees Fahrenheit

T_d - dew point in degrees Fahrenheit

R_s - solar radiation in langleys per day

The results of a 10% precipitation increase (given by the monthly values in Column 2) indicate that the evapotranspiration rates would decrease in this area by about 7%. This figure is arrived at by comparing the normal, annual evapotranspiration rates (37.7"/year) to the rates with a T_d increase and a T and R_s decrease (35.1"/year) suggested in Column 2.

It is difficult to speculate on the effects of a 7% evapotranspiration decrease. An estimate could be made of the annual net gain of water for a lake in Area 2 by multiplying the surface area by the difference between the modified estimation of potential evapotranspiration and the normal estimate. A lake of 10 square miles would have an estimated net gain of about 450 million gallons. The

TABLE B

ESTIMATION OF POTENTIAL EVAPOTRANSPIRATION

FOR AREA 2 (IN INCHES) WITH PARAMETERS MODIFIED

	1	2	3	4	5	6
Month	Normal	T dec 1°F T_d inc 2°F R_s dec 15 ly/dy	T inc 1°F T_d dec 2°F R_s inc 15 ly/dy	T dec 1°F	T inc 3°F	T dec 3°F
JAN	.7	.6	.9	.7	.9	.6
FEB	1.2	1.0	1.3	1.1	1.3	1.0
MAR	2.2	2.0	2.4	2.1	2.5	2.0
APR	3.4	3.1	3.6	3.3	3.6	3.1
MAY	4.8	4.5	5.0	4.7	5.0	4.5
JUNE	5.7	5.5	6.0	5.6	6.0	5.4
JULY	6.0	5.7	6.3	5.9	6.3	5.7
AUG	4.8	4.5	5.1	4.7	5.1	4.5
SEPT	4.1	3.9	4.3	4.0	4.4	3.8
OCT	2.6	2.4	2.9	2.6	2.9	2.4
NOV	1.3	1.2	1.5	1.3	1.5	1.1
DEC	.9	.7	1.0	.8	1.0	.7
ANNUAL	37.7	35.1	40.3	36.8	40.5	34.8

TABLE B (continued)

Month	7 T_d inc 5° F	8 T_d dec 5°F	9 T inc 3°F T_d dec 5°F	10 T dec 3°F T_d inc 5°F	11 T dec 3°F T_d inc 5°F R_s dec 15 ly/dy
JAN	.5	.9	1.0	.4	.4
FEB	1.0	1.3	1.4	.8	.8
MAR	2.0	2.4	2.6	1.8	1.7
APR	3.2	3.5	3.8	2.9	2.8
MAY	4.6	4.9	5.2	4.2	4.2
JUNE	5.5	5.9	6.2	5.2	5.1
JULY	5.8	6.2	6.4	5.5	5.4
AUG	4.6	5.0	5.3	4.3	4.2
SEPT	3.9	4.3	4.5	3.6	3.5
OCT	2.4	2.8	3.0	2.2	2.1
NOV	1.1	1.5	1.7	.9	.9
DEC	.7	1.0	1.2	.5	.5
ANNUAL	35.3	39.7	42.3	32.3	31.6

actual net gain may be somewhat less than this value due to ice on the water surface in the winter. An ultimate result of decreased potential evapotranspiration in the fall and winter might be more snow accumulation and more runoff in the spring.

CHAPTER III.
SOIL MOISTURE AND GROUNDWATER

A. Infiltration

Infiltration is a process by which rain enters the soil. Infiltration capacity describes the maximum rate at which water can enter a given soil under given conditions.

Infiltration depends chiefly upon the chemical and physical properties of the sediment as well as characteristics of precipitation, vegetation, and topography. The following factors are most significant when discussing the effects of precipitation modification on infiltration rates:

1. Type of soil
2. Soil temperature
3. Plant and animal action in the soil
3. Rainfall intensity
5. Snow cover
6. Vegetation
7. Slope of the surface

Soils of the gravelly, sandy type are the most porous and provide the highest infiltration rates. Such soils are most prevalent in Areas 4 and 5 in Figure 5. In areas where the soil layers are of unequal permeability, the infiltration rate is controlled by the least permeable layer.

Soil temperatures also affect infiltration rates. Free, Browning, and Musgrave (1940) found that infiltration rates tend to rise with increasing sediment temperatures. This is due to the decreasing water viscosity with increasing temperatures. Theoretically, within typical temperature ranges, the infiltration rate should approximately double with a 50°F increase in water temperature. However, infiltration can occur only as fast as the displacement of an equal volume of air within the soil. While the viscosity of water decreases as temperature increases, the viscosity of air increases with increasing temperature. Thus, raising the temperature increases the inflow of water, but

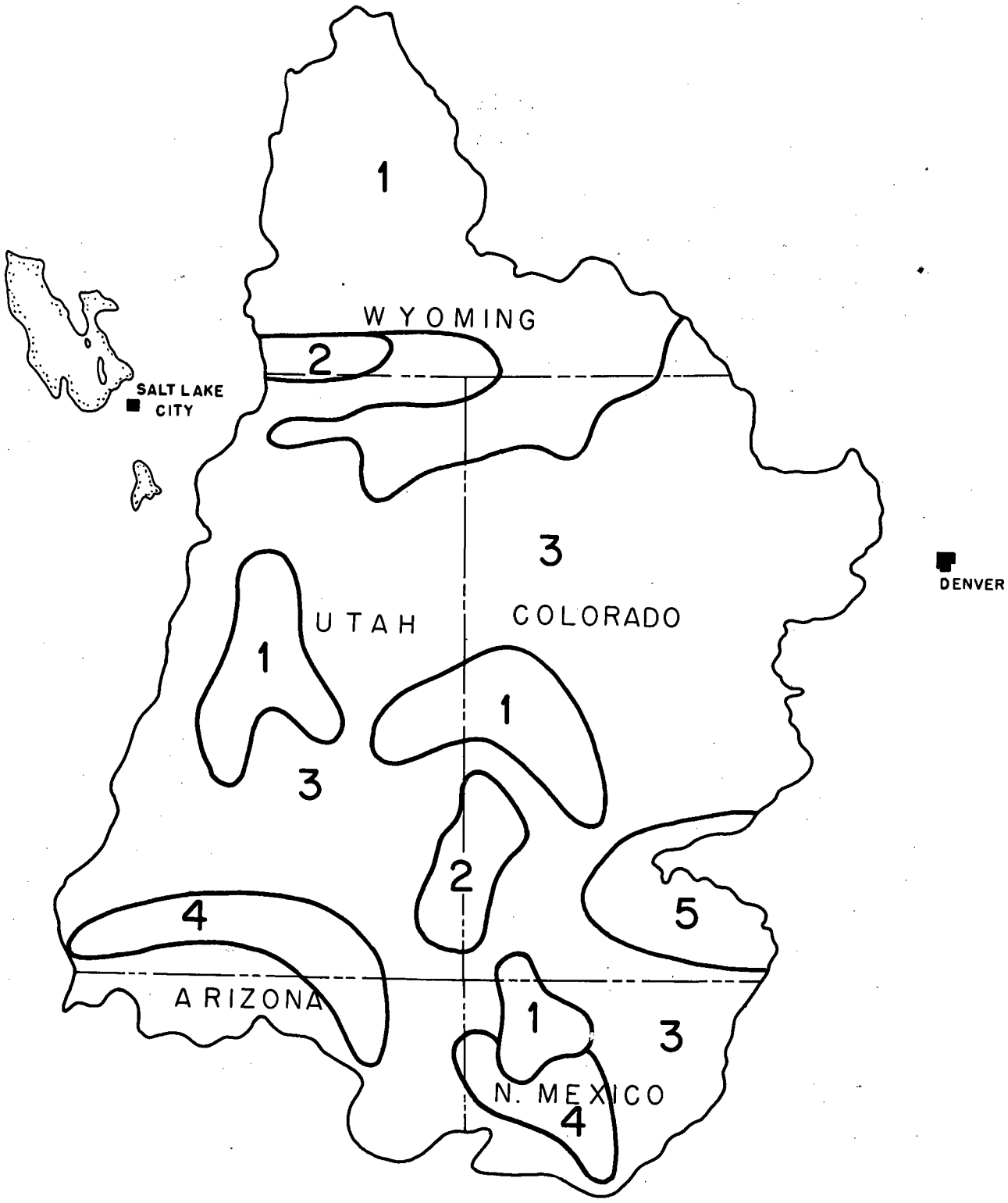

Figure 5

Soils Map

(1) Gray Soils -- Arid Regions; (2) Dark Brown Soils -- Cool, Temperate, Subhumid Regions; (3) Shallow Soils of Imperfectly Weathered Rock; (4) Brown Soils -- Warm, Temperate, Semi-Arid Grasslands; (5) Grayish Brown Leached Soils -- Temperate, Humid, Forested Regions

decreases the rate at which air escapes. With this opposition of viscous forces, the effect of temperature upon infiltration is reduced.

Plant and animal action within the soil is one further factor influencing the infiltration rate. Decaying roots leave channels throughout the root zone at varying depths depending upon the vegetation type. Certain animals, such as gophers and earthworms, may considerably increase the permeability of the soil, and hence, the infiltration rate.

The infiltration capacity of the soil is at a maximum when rain begins, but decreases rapidly as a result of the packing of the soil surface by rainfall impact and inwashing of fine materials through the soil surface openings. Typically, the infiltration capacity may drop from 1 inch per hour or more at the beginning of the rainfall to ½ inch per hour or less within an interval of 1-3 hours. If the rain continues, the uppermost sediments become saturated, and infiltration capacity slowly decreases to a minimum.

If the rainfall intensity remains below the infiltration capacity of a particular area, all rainwater will be absorbed. Short, intense bursts of rain, such as summer thundershowers, will result in a decrease of infiltration capacity to its minimum value and thus excess precipitation will become runoff. A longer-lasting rain of less intensity would result in greater soil infiltration, especially if the soil is initially quite dry.

The infiltration capacity begins to return to its maximum value as soon as the rain ends. This process usually takes one day or less for sandy soils, and often several days for clays and fine-textured soils. Seasonally, the maximum and minimum infiltration capacities for a given soil remain fairly constant.

The presence of snow on frozen ground is another important factor in determining infiltration rates. Frost in the ground may either increase or decrease the

infiltration capacity, depending upon the soil moisture condition. If the soil has low moisture content, it may become granulated and more permeable. Soils with high moisture content may become nearly impermeable if concrete frost is formed. A snow cover often maintains the same soil structure that was present at the time the cover was formed; thick snow cover usually prevents freezing in the ground. The soil may remain near saturation if there is snowmelt near the surface when these conditions prevail.

Vegetation also plays a major role in infiltration capacities. By using water, vegetation allows for an increase in the soil's capacity to store water.

Vegetation also helps to preserve the porous structure of the soil. Additionally, the ground is well-protected from direct impact of raindrops which would otherwise reduce the infiltration rate through soil packing. Thus, any vegetation cover will tend to increase infiltration. The following data, compiled by Underhill (1962) at the San Dimas Experimental Forest in Southern California, compares the benefits of different types of vegetal cover on infiltration:

Table C. Effects of Vegetation on Infiltration

Vegetation	Total Annual Infiltration (inches)
bare ground	7.7
pine forest	15.1
grass	16.7
buckwheat	17.2
scrub oak	17.4

Another factor involved in determining infiltration is the slope of the surface. For slopes less than 16%, infiltration capacity is independent of the slope. For slopes greater than 16%, runoff increases while infiltration capacities decrease (Neal, 1938).

The effects of weather modification on infiltration are difficult to assess because determination of the

infiltration rate itself is very complicated. The factors involved in these determinations cannot be duplicated in a laboratory; these measurements must be taken at the research area. Two methods are used: 1) analyzing rainfall and runoff from natural drainage basins, and then computing the infiltration rate from the data; and 2) using an infiltrometer or other similar instrumentation. Given a good record of surface runoff, an accurate rain gauge, and other rainfall data, it is possible to ascertain the average areal infiltration capacity over a drainage basin with good accuracy. However, the Upper Colorado River Basin does not have uniform soil or vegetation types; consequently, an accurate infiltration rate typical of the entire basin cannot be determined. It would be necessary to collect data from many stations just to obtain infiltration rates for smaller subbasins.

It is evident from the preceding paragraphs that there are many variables involved in determining infiltration rates and capacities as well as many complex interactions among these variables. Musgrave and Free (1936) concluded that a specific infiltration rate for a particular type of sediment is virtually nonexistent and that measured rates are primarily of comparative value.

The variability of the parameters which affect infiltration rates suggests that the best time to modify precipitation to increase actual infiltration is in late spring and summer. At this time of the year, vegetation is the most dense, soil temperatures are at a maximum, animal action is at its peak, and the ground is unfrozen.

Increased precipitation would infiltrate most rapidly into the soils of the San Juan Division because this Division has the greatest amount of favorable sandy soil types and the driest initial conditions. The ground is least likely to be frozen in this Division, especially in the south. In addition, the San Juan Division has the

gentlest slopes and surface runoff would not reduce infiltration significantly.

B. Soil Moisture

Moisture in the soil is an important factor in understanding the hydrology of a watershed. Hydrologists classify the earth's mantle into the zone of aeration and the zone of saturation, with the water table separating these two zones. Water stored in the zone of aeration is referred to as soil moisture (see Figure 6). The soil moisture storage capacity is dependent upon soil type, depth and texture, root capacity, bulk density, organic matter, colloidal material, stone content, and soil stratification.

Soil depth affects soil mositure. Other factors being equal, deep soils are capable of holding more moisture than shallow soils. For deep-rooted plants in subhumid and semiarid regions this is of practical significance. The texture, structure, and organic matter content all determine the quantity of moisture a given soil can retain. As the texture becomes finer, there is a general increase in soil moisture storage. A well-drained mineral soil with 5% organic matter will probably have a higher available moisture capacity than a comparable soil with only 3% organic matter. This is not due to the moisture holding capacity of the organic matter, but rather to the favorable influence of organic matter on soil structure and porosity. The greater the soil's organic content, the more readily the soil can be broken down into smaller aggregates capable of holding more moisture. Soils which are high in colloidal materials will hold more water than will sandy soils or those low in clay and humus.

Soil stratification or layering can markedly influence the available water and its movement in soil. For example, impervious layers can drastically slow down the rate of

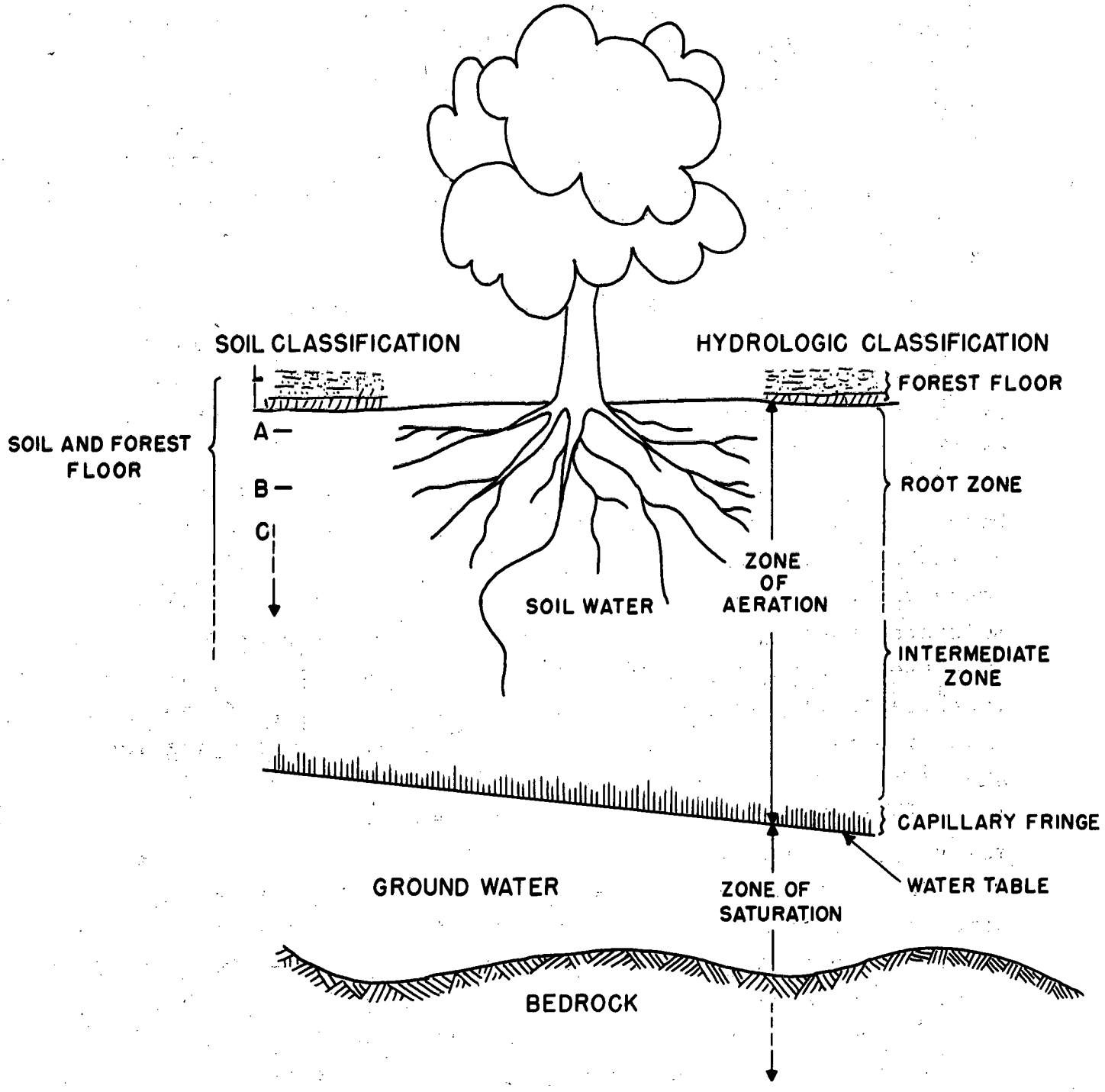

Figure 6
Classification of Weathered Mantle
(Hewlett and Nutter, 1969)

movement of water in the soil thereby influencing total soil moisture capacities. Finely-textured layers can also act as barriers to soil moisture movement downward from sandy layers above.

Stony soils store a much smaller quantity of water than a comparable amount of stone-free soil. This is explained by observing that solid stone within a soil can contain no available water.

In evaluating the effect of a 10% increase in annual precipitation on the soil moisture of the Upper Colorado River Basin it is important to examine the soil properties of the areas receiving the precipitation and the objectives of the modification.

If an objective of increasing the precipitation in the Upper Colorado River Basin is to have more water locally available in the soil for vegetation use, care should be taken to increase precipitation over soils with good soil moisture capacity. If the modification objective is to increase streamflow, precipitation should fall over impermeable, low moisture capacity soils. Lastly, if the objective is to directly raise the water table, precipitation should be modified over rocky or rough-textured soils. These soils have high infiltration rates and low soil moisture content.

The Upper Colorado River Basin is a region with a diversity of soil types, and precipitation increases can affect these soils in different manners. The Upper Colorado River Basin is separated into five soil types, each with individual soil moisture characteristics (see Figure 5).

Area 1, a gray soil and arid region, has a moderate soil moisture capacity. In the flat land regions of this area a good percentage of the precipitation is retained in the soil.

The brown soils of Area 2, a cool semi-arid grassland region, have moderate to good soil moisture capacities. A

good deal of the increased precipitation in this area would be retained in the soil and would be used locally by vegetation.

Soil moisture capacity of Area 3 is very low. This area consists mostly of shallow soils of rough texture. Increased precipitation over these areas would either directly raise the water table over level terrain, or rapidly increase runoff over steep terrain.

Area 4 contains brown soils and warm, semi-arid grasslands. These soils have moderate soil moisture capacities and infiltration rates. The soil layers are characteristically deeper but quite similar to Area 2.

Area 5 is a region of warm, humid forests. The soils here are mature, high in organic materials, and relatively deep. The infiltration rates are high and the soil moisture capacity is quite high. Increased precipitation in this area would contribute a large amount of water to the soil moisture reservoir.

Most of the soils in the San Juan Division have high moisture capacities. A good deal of the increased precipitation in this region would be retained by the soils and used locally by vegetation. The Green Division would be capable of retaining moderate amounts of water in the soil moisture reservoir where the land is level. The Grand Division is least capable of storing water in the soil because most of soil in this Division is shallow and rocky.

C. Groundwater

The water table is the upper limit of the ground completely saturated with water. Fluctuations in the depth of the water table indicate changes in groundwater storage. The amount of groundwater storage depends primarily on groundwater recharge, groundwater evapotranspiration, and groundwater runoff.

Groundwater recharge comes from water which has

percolated through the soil to the water table. This water originates from either snowmelt or precipitation that has infiltrated the soil. Groundwater evapotranspiration is that water used by plant roots and passed into the atmosphere by the plant leaves. Evapotranspiration from the groundwater reservoir is, in general, a function of the season and the mean groundwater stage. Groundwater runoff is that part of the groundwater which flows into streams. Groundwater runoff is generally at a maximum during spring and early summer and is minimized in late summer and fall. These three variables cause fluctuations in the water table over time periods ranging from hours to seasons. Hourly variations are observed when the water level is close enough to the surface to be affected either by evaporation or transpiration.

In order to understand how increased precipitation will affect groundwater storage, the interactions among recharge, evapotranspiration, and runoff in the ground will be examined.

In the Upper Colorado River Basin meltwater is the greatest source of groundwater recharge. Snow in this region falls on unfrozen ground in the early fall. As the snowpack increases through the winter, snow melts at ground level and seeps into the ground. This recharge mechanism occurs from November to April.

Groundwater evapotranspiration is very small during this period. Consequently, most of the water which has infiltrated will reach the water table if the soil moisture deficit has been satisfied. However, from November to April, infiltration decreases due to lower soil temperatures and reduced flora and fauna activity. In regions of the Upper Colorado River Basin where groundwater evapotranspiration is significant, these off-setting factors must be examined when determining the effectiveness of increased snowpack as related to increased groundwater storage.

During the remainder of the year, groundwater can be

recharged by increasing rainfall. Increased rainfall, however, would contribute more to streamflow than to groundwater recharge because (1) most of the precipitation occurs as heavy showers resulting in heavy surface runoff, and (2) groundwater runoff is a maximum.

Ideal conditions for increasing groundwater recharge are found in the mid-western part of the San Juan Basin. This area has a high infiltration capacity and a high potential for soil moisture storage.

D. Groundwater Storage

The Upper Colorado River Basin is not abundant in groundwater productive aquifers. In general, the Basin contains rocks of low permeability. This presents a major problem in determining what effect increased precipitation would have on groundwater storage.

In the Green Division, groundwater occurs in deposits of glacial origin in the mountains. Groundwater reservoirs are abundant in the mountainous region. In the interior of the Division groundwater can be found in deeply buried, permeable rocks. Shallow groundwater is also present in the interior region. Significant quantities of shallow groundwater occur in deposits of glacial outwash in the valleys of the New York River and its tributaries. Shallow groundwater can also be found in deposits of river alluvium that border and underlie other streams in the Division.

In the Yampa River watershed, groundwater is found mainly in the headwaters. Underlying this region are permeable rocks which provide recharge into the groundwater reservoirs. The low precipitation over the interior of the Yampa River drainage basin, however, provides little opportunity for groundwater recharge in this area. In addition, the rocks exposed over the interior of this drainage basin are poor aquifers.

The Lyman-Mountain View area of southwest Wyoming is representative of the aquifers of the North Green Division.

In this area, the water table ranges from zero to fifty feet below the land surface. Major stream valleys and much of the uplands in the Lyman-Mountain View area are underlain by deposits of highly permeable rocks. These deposits are capable of yielding significant quantities of groundwater when saturated.

The Utah portion of the Green Division has fewer productive aquifers. The rocks of the Wasatch and the Uinta ranges and other mountains in this area are of low permeability and of little significance as productive aquifers. The rocks found in strips on the northern and southern sides of the Uinta Mountains hold some promise as productive aquifers.

The Colorado portion is the final area of the Green Division to be covered. In the mountainous areas of the extreme northwestern corner of the state, the rocks are generally dense and of low permeability. These rocks contain only small quantities of water principally in the weathered and fractured zones. Consolidated sedimentary rocks underlie small areas and are not significantly better water bearers. Alluvium is present along streams and in some basins. Bedrock forms a moderately productive aquifer along some stretches of the Yampa and Green Rivers. Alluvial aquifers are a potential source of some groundwater yield.

In the Grand Division the major area of interest is the Colorado Plateau. The rock formations and water-bearing aquifers are basically uniform throughout the plateau area. In this region the plateaus are deeply dissected; water lies at great depths. Recharge conditions in this area are generally unfavorable because potentially high yielding aquifers are covered by rocks of low permeability. The exposure of most of the water-bearing strata are within canyon walls (areas of discharge rather than recharge).

In the San Juan Division natural recharge to the groundwater reservoir occurs in the mountainous regions

where precipitation is abundant. Sandstone, which is an excellent aquifer, underlies most of the non-mountainous sectors of this region. Precipitation is low here and very little groundwater recharge occurs. Increased precipitation in the non-mountainous sectors would be most effective in increasing groundwater storage. Poor areas for increasing groundwater storage are found in the New Mexico portion of this Division where finely grained rocks are commonly found. Other poor regions for increasing groundwater storage include the Animas and Los Pinos River Basins which both contain a significant amount of impermeable rock.

CHAPTER IV.
STREAMFLOW

A. Introduction

The stream system of the Upper Colorado River Basin rises near the eastern part of the Basin from 13,000-foot Mt. Richthofen on the Continental Divide and then flows southwestward to Lee's Ferry, Arizona. The largest tributary, the Green River, rises in the Wind River Range at the north end of the Basin and flows southward to join the Colorado River sixty miles south of the town of Green River, Utah. The San Juan River, the second largest tributary, rises on the western slope of the Continental Divide in the southeastern part of the Basin. The river flows westward to join the Colorado about 75 miles west of Bluff, Utah.

The principal tributaries of the Colorado River above the Green River are the Eagle River, Roaring Fork River, Gunnison River, and Dolores River. The chief tributaries of the Green River are New Fork River, Big Sandy Creek, Black's Fork, Henry's Fork, Yampa River, White River, Duchesne River, Price River, and San Rafael River. The principal tributaries of the San Juan River are the Navajo River, Los Pinos River, Animas River, and the La Plata River. Other tributaries entering the Colorado below the Green River are the Dirty Devil, Escalante, and Paria Rivers (Iorns, et al, 1965).

The streamflow characteristics of the Green and Grand Divisions and of much of the San Juan Division are similar with few notable exceptions. As the snow melts in the late spring and early summer the streams rise and then subside as the snow supply is exhausted. Usually, by late July, the perennial streams flowing from the mountains subside to base flow, which prevails until the snowmelt period begins the following spring when the cycle is

repeated. Summer precipitation, usually in the form of thunderstorms, contributes very little to streamflow because it is returned to the atmosphere through evapotranspiration.

This section of the report will deal with the effects increased precipitation would have on the streamflow characteristics of the Upper Colorado River Basin. These effects will vary depending on the physiographic features of the area in question. In this report the effects of topography and vegetation on streamflow will be considered; in addition, the probable response of stream channel geometry to an increase in streamflow as a result of cloud seeding will be discussed.

B. Topography and Streamflow

Streamflow variations in the Upper Colorado River Basin can generally be accounted for from topographic influences. Where relief is rugged, precipitation amounts are generally high because of upslope effects. More snow falls in winter in these areas, producing the spring maximum in streamflow. Where elevation is low and the surface relatively smooth, little precipitation falls and little or no spring streamflow maxima occur.

The Green Division is bounded by a series of steeply sloping mountain ranges. Winter snowfall is heavy and nearly 50% of the annual precipitation is lost to runoff--an event which is maximized in the spring (Iorns, et al., 1965). Because of the influence of these mountain ranges, most of the streams in Green Division follow the regional flow patterns. In the interior of the Division there are broad river valleys and somewhat gentler slopes. In the flatlands of the interior, only 15-30% of the annual precipitation becomes runoff (Iorns, et al., 1965). The effects of this gentle topography are felt in the streams approaching the Green River from the east. These streams

have their origin on the East Travaputs Plateau where snowfall is light; in these streams there is no sharp spring maximum. Some of the smaller streams have intermittent flow, carrying water only during the early spring and after summer thundershowers.

In the Grand Division topography and streamflow characteristics are very similar to those in the Green Division. In the upper levels of the Grand Division landforms are quite steep; as much as 50% of the annual precipitation is lost to runoff. Approximately 75% to 85% of the runoff is a result of snowmelt (Grant, 1969), and the remainder is a result of rainfall on steep slopes. Because of the mountains' dominating effect on streamflow, the smaller subbasins of the Grand Division follow the general streamflow pattern of the entire Basin with one exception. The subbasin between the Gunnison and Green Rivers, in which the Dolores River is the main stream, is at a lower elevation than the rest of the Division; little snow accumulates here through the winter months. In this subbasin no sharp spring maximum in streamflow exists, and many streams are intermittent and carry water only after infrequent summer thundershowers. These summer storms are usually of short duration and small areal extent, but are sometimes strong enough to produce flash floods.

The San Juan Division is bounded by mountain ranges to the north, but much of the southern half of the Division is flat and arid. Streams running from the mountains reach peak flow during spring snowmelt, but this peak is only a reflection of part of the total contribution to streamflow. The remainder of the streamflow is generated in the lower levels of the Division where intense summer thundershowers fill the ephemeral streams and gullies. Though the lower levels receive, on an average, only eight inches of precipitation annually, most of this precipitation falls from heavy, scattered summer thunderstorms. Each shower

contributes a substantial amount of water to streamflow causing a secondary peak during the summer.

In the dormant season the waters of the San Juan River flow from the mountains to the stream's juncture with the Colorado River. However, during the growing season, most of the water is diverted for irrigation purposes, leaving the downstream channels dry except during storms.

C. Vegetation and Streamflow

Vegetation tends to reduce streamflow by allowing for increased infiltration, transpiration, and interception. Infiltration is discussed in detail in Chapter III, and transpiration and interception are discussed in Chapter II.

In summer, vegetation density is at a maximum and vegetative effects are most pronounced. In winter, vegetation effects are not significant; infiltration is low because the ground is generally frozen, transpiration is near zero, and interception is small.

Increasing the precipitation could alter the vegetation-streamflow interactions most significantly in areas of marginal vegetation growth. In areas where vegetation density is enhanced by increased precipitation, there will be an increase in transpiration. Increased transpiration would place a stress on the available moisture of an area unless the modification of precipitation is sufficient to maintain substantial soil moisture and streamflow levels.

Important also is the spread and intensification of plant diseases. Weather modification during the growing season would most likely alter disease occurrence patterns. Cooper and Jolly (1969) found that "plant diseases in which the causal agent is dispersed to above ground parts of the host will be most strongly affected."

Increased precipitation would result in a deeper snowpack; vegetation growth could be altered in many ways.

In mountainous areas, vegetation growth beneath deep snow cover differs from growth in areas of average snow cover. Woody vegetation is often more abundant within, and just below, zones of drifted snow than in adjacent areas where snow does not accumulate. This vegetation growth variation is a result of melting snow which recharges soil moisture; deeper snowpacks remain on the ground longer, maintaining maximum plant growth well into the summer. Snowpacks at higher elevations, however, may persist so late into the growing season that woody species cannot survive and reproduce. The length of time that snow remains on the ground depends on such weather factors as cloudiness, air temperature, and atmospheric humidity during the melt period.

Triggering snowfall as a means for increased runoff could change vegetation growth in an area through increased growth of fungi under the snow. Cooper and Jolly (1969) found that "abundant and lasting snow falling before the ground is frozen creates a favorable microclimate for low-temperature parasitic fungi such as 'furarium,' 'sclerotinia,' and typhula.' If the snow is deep enough to remain on the ground well into the spring, plants are highly susceptible to injury by these snow mold or snow blight organisms, apparently as a result of oxygen deficiency and carbon dioxide excess caused by respiration under compact snow." Other snow molds can cause damage to spruce, especially seedlings subjected to prolonged snowcover. An appreciable increase in snow amount and duration would have adverse effects on spruce regeneration, particularly in areas where spruce stands are marginal.

Increased snow accumulation could also have an effect on insect populations that affect vegetation. Cooper and Jolly (1969) found that "artificial increase of snowfall is likely to affect insect populations somewhat differently than increase in rain alone. The amount and duration of snowcover are important in the overwintering of many

insects, and changing these quantities may alter insect numbers." Increases or decreases in insect population could have important effects on the insect-vegetative interactions peculiar to that region.

D. Modification of Vegetation and Weather to Improve Streamflow

Attempts to increase streamflow by treating vegetation cover in order to decrease evapotranspiration have met with varied success. While it is true that a reduction of evapotranspiration is likely to increase the amount of water remaining on a watershed, it is also true that evapotranspiration proceeds at its maximum potential rate whenever water is readily available. When sufficient surface water is available, reducing potential evapotranspiration will reduce actual evapotranspiration. Vegetation treatments to reduce potential evapotranspiration would be effective in increasing streamflow. However, the situtation is different under dry conditions where actual evapotranspiration is less than potential. In this case, reducing potential evapotranspiration will not effect actual evapotranspiration. This means that treating vegetation does not help streamflow in areas where it is needed most.

E. Stream Geometry

Most of the water which is supplied to the Colorado River comes from headwater streams at higher elevations. In these headwater regions the underlying rock types are igneous and metamorphic. Specifically, rock types are schist, gneiss, granite, basalt, and diorite, all of which do not weather easily (Iorns, et al., 1965). There is little short-term erosion and consequently little deposition of material in the streams here. The loose bed material present is either coarse or fine gravels (Leopold, Wolman, and Miller, 1964). The weighted-average concentration of the dissolved solids in streams at any point in the

headwater regions never exceeds 100 parts per million and seldom exceeds 50 parts per million (Iorns, et al., 1965). In streams with relatively large gradients, suspended particles are usually deposited further downstream where the gradients are less.

The streams in each division fall rapidly off the mountains, merging eventually with other headwater streams. As the streams flow off the mountains, they flow through regions of foothills and then level off across the plateaus. In the Green Division, the foothill region is small while the plateau region is extensive, covering about 80% of the land area. In the Grand Division, where mountain and foothill regions are more extensive, the plateaus account for about 70% of the land area. In the San Juan Division, the foothill region is small and again the plateau region is by far the most extensive, covering approximately 80% of the area. The rock types in the foothill regions are mostly limestones, quartzes, shales, and some sandstones which, in general, are more susceptible to weathering than the rocks in the headwaters. The plateaus are composed largely of sandstone, siltstone, and shale, and are even more easily weathered (Iorns, et al., 1965). The dry washes surrounding the plateaus enable the plateaus to drain. These dry washes flow only during heavy rains when tons of sediment are carried to the main stream channels. The suspended sediment yield increases in the basins downstream, supporting the fact that the majority of the sediment comes from the plateau regions (Leopold, Wolman,and Miller, 1964).

Thus, throughout the Upper Colorado River Basin, there are three major zones: mountains, foothills, and plateaus. In the mountains, the stream gradient is very high. The gradient decreases in the foothills and is very low in the plateaus.

If weather modification were to be undertaken, the effects it would have on stream geometry must be considered.

F. Increases in Stream Discharge

Consider first increases in stream discharge in the headwater region. This is the main source region for the Colorado River. Because winter weather modification would increase the snowpack in the headwater region, stream discharges here would be enhanced. An increase in stream water discharge, however, would not appreciably alter the stream geometry in the headwater region itself; the rocks of the headwaters are not easily eroded. Even in the foothill zone, precipitation increases and the resultant streamflow increases would probably have little effect on stream geometry. Perhaps the sole difference would be a decrease in stream gradient which would decrease by compensating for increased streamflow. However, in the plateau zone, the effects of increased precipitation in the headwaters would likely become significant. Assuming that the streams of the plateaus approximate fluvial streams, the stream geometry relations found by Schumm (1969) in heterogeneous watersheds of the Midwest appear relevant to this study. His equations indicate that an increase in average yearly stream discharge would increase the bankfull width, the maximum depth, the stream's width-depth ratio, and the meander wavelength. The stream's gradient, however, would decrease.

G. Increased Snowpack and Flooding

Increases in snowpack depth by winter cloud seeding must next be emphasized; the area over which the snowpack is increased is important here. Each year, with the melting of the snowpack, there is usually minor flooding. The severity of the flooding depends upon the intensity of the thaw and the amount of water contained in the snowpack. Increasing the snowpack tends to enhance the magnitude of flooding potential. Flooding always causes scouring and filling of a stream channel; bars are lowered, and the

residuum is deposited downstream, usually in reservoirs (Leopold, Wolman, and Miller, 1964). Increased stream velocities associated with flooding relocate dunes and ripples in the stream bed. More permanent structures such as large rocks and boulders may be moved. Thus the scouring and filling of stream channels, the depositing of materials downstream, and the increased streamflow velocities associated with flooding all must be considered before raising the snowpack levels.

The preceding discussion warrants consideration by all interests who intend to increase precipitation in the Upper Colorado River Basin. Stream geometry is a function of stream gradients and stream discharge, and although tangible changes in streamflow characteristics take many years to form, the more immediate effects of increased precipitation are usually felt. Particularly, flooding has been seen to occur with the melting of increased winter snowpacks, especially in the headwater region. Suspended sediment yields downstream increase with increased streamflow. This may pose problems for downstream reservoirs. Schumm (1969) found that other parameters changed as well; quantities such as stream depth, width, and meander wavelength slowly respond. The complex interaction of natural streamflow characteristics and increased stream water must be judged in all instances.

CHAPTER V.

SOCIAL, ECONOMIC, AND LEGAL EFFECTS OF WEATHER MODIFICATION ON THE HYDROLOGIC CYCLE

A. Social and Economic Effects

1. Introduction

In discussing the changes in the hydrologic cycle that weather modification could produce, it is necessary to include the social and economic effects such changes might have. Weather modification would have the greatest influence on two variables in the hydrologic cycle: depth of the snowpack and runoff. This discussion deals with the effects of changes in these two variables only, and with the socio-economic advantages and disadvantages of cloud seeding in the Upper Colorado Basin. Unless specified otherwise, it will be assumed that cloud seeding will produce a 10% increase in precipitation throughout the year.

2. Avalanches

Avalanche occurrence is closely related to the condition of the snowpack. The widespread danger from avalanches and the effect of precipitation modification on avalanches will be considered here.

Avalanches have been recognized as a threat in the Rocky Mountain area since the mining boom of the nineteenth century filled mountainsides with prospectors. Alta, Utah, provides the location for one of the first serious avalanches experienced in America. Montgomery Atwater (1968) tells the story:

> "In the 1860's, Alta was one of the gaudiest silver camps of the West. If the legends of the time are true, it was also unique for a mining camp in that no women, virtuous or otherwise, were allowed to stay in it in winter ... Between exhaustion of the richest veins of ore and the demonetization of silver, Alta was already on the downgrade when it was virtually obliterated in the winter of 1864 by a combination of avalanches and their fiery aftermath, which broke out around overturned coal and wood stoves."

From these ruins, Alta rose to become the birthplace of avalanche research in the United States. This rise would not have been possible without the introduction and rapid advance of skiing into the Alpine Zone in 1946 at Alta. The responsibility for the safety of the skiers fell to the United States Forest Service, which had jurisdiction over most of the ski lands west of the Mississippi. The Forest Service was thus brought to the forefront of avalanche research and has since published a thorough analysis of avalanche causes and controls (U. S. Department of Agriculture, 1968).

Today the number of persons and enterprises affected by avalanches is constantly increasing, and the threat to life and property is greater than ever before. Avalanches endanger mining and logging operations, railroads, power and telephone lines, pipelines, highways and highway maintenance, reclamation and flood control projects, and ski resorts. The Colorado State Highway Department, Colorado Power and Light, The Governor's Committee of Colorado, and the National Ski Association have been among the organizations requesting advisory assistance from the avalanche unit of the Forest Service.

Due to the interest of these organizations and to the widespread dangers involved in avalanches, the possibility of increasing avalanche frequency and intensity by increasing the snowpack through weather modification must be investigated.

For the purpose of this report, avalanches may be divided into two groups: direct-action and delayed-action. Direct-action avalanches are basically the result of a new fall of snow and occur during or immediately after a storm. Delayed-action avalanches are caused by internal modifications in the structure of the snowpack brought about by wind action and temperature change in the days following a storm.

This analysis will deal primarily with direct-action avalanches because (1) they account for 80% of the avalanches large enough to endanger life and property, and (2) they are by far the most sensitive to weather modification (U. S. Department of Agriculture, 1968). This does not mean that delayed-action avalanches are insignificant; they do pose a threat, especially in the High Alpine regions, where they are most frequent. One type of delayed-action avalanche, the climax avalanche, is probably the most severe type; but delayed-action avalanches are not affected by as many weather modification sensitive variables as are the direct-action avalanches that will be dealt with here.

The Forest Service lists ten contributing factors in the occurrence of important avalanches (U. S. Department of Agriculture, 1968):

1. Old snow depth
2. Condition of the base
3. New snow
4. New snow type (crystal type)
5. New snow density (on the ground)
6. Snowfall intensity
7. Precipitation (liquid water equivalent) intensity
8. Settlement
9. Wind
10. Temperature

Of these ten, four are very sensitive to weather modification: old snow depth, new snow depth, snowfall intensity, and precipitation intensity. These four would have considerably more effect on direct-action avalanches if cloud seeding produced more snow.

The first factor, old snow depth, is merely the amount of snow on the ground before a new storm begins. A precipitation increase would enhance its importance, because there most likely would be more snow on the ground

during the winter. The old snow depth becomes important to increased avalanche frequency when it is deep enough to cover surface irregularities along the potential path of the avalanche. In the Upper Colorado River Basin, surface irregularities can be smoothed by as little as six inches of snow on a grassy slope, or by as much as six feet of snow on a boulder-strewn slope. On the average, 2-3 feet of snow is needed to cover surface irregularities. In general over the Basin, the deeper the old snow, the more likely avalanches are to occur.

If cloud seeding resulted in extra snowfall from a storm, new snow depth, the second factor, would clearly be enhanced as an avalanche cause. A large amount of new snow is the most important trigger of direct-action avalanches and the potential for these avalanches increases with increasing new snow depth. Snowfalls greater than twelve inches are especially dangerous in the Basin, and in the High Alpine regions of Colorado, amounts of four to five inches can create avalanche conditions (U. S. Department of Agriculture, 1968).

A factor closely related to the amount of new snowfall is the intensity of the snowfall. Snow of light or moderate intensity (measured in inches per hour) will usually settle to a stable configuration, but high rates of snowfall will often create instability faster than settlement can reduce it. More than one inch per hour will generally result in development of unstable conditions in most areas, and this cutoff is one 1/2 inch per hour in the High Alpine regions (U. S. Department of Agriculture, 1968).

The last factor is precipitation intensity, the rate at which mass is being deposited on the slope. It is more highly correlated with avalanche frequency than is snowfall intensity, but is more difficult to measure. There is a very high correlation between precipitation greater than

one-tenth of an inch per hour (melted) and avalanche frequency when winds are strong (above 25 mph) and over one inch falls (U. S. Department of Agriculture, 1968).

Although these factors have been treated separately, they are interrelated and it is their combined effects that produce avalanches. Because four of the ten factors considered important by the Forest Service would be enhanced by a precipitation increase, it can be concluded that cloud seeding will increase the possibility of a favorable combination for avalanche occurrence.

Although this is a rather subjective analysis and more exact data is needed on the separate influences of each factor, it is safe to say that cloud seeding in the Upper Colorado River Basin in winter will increase the avalanche hazard. The threat to life and property involved in this hazard would be one of the chief detriments of a cloud-seeding program.

3. Highway Maintenance

Another operation sensitive to changes in the snowpack is highway maintenance. Clearly, if snowfall is increased, highway department snow removal problems and costs would also increase.

The Colorado State Highway Commission has kept cost records since 1962 of snow removal, avalanche control, snow fence repair, and sanding. Sanding will be ignored because sanding costs have little relation to total snowfall and are relatively constant from year to year. Excluding sanding, snow removal represents 90% of snow-related costs (U. S. Bureau of Reclamation, 1969), so avalanche control and snow fence repair can also be neglected. Snow removal involves not only clearing away direct snowfall from the highways, but also removing snow deposited by avalanches.

The University of Colorado in conjunction with the Bureau of Reclamation investigated the relationship between snowfall and snow removal costs and found that a 25% increase

in the average snowpack would produce about a 15% increase in snow removal costs (U. S. Bureau of Reclamation, 1969). They also found that "from a weather modification standpoint snow removal capabilities should be well within the range of normal planning to cover years ... up to perhaps 150% of average" (U. S. Bureau of Reclamation, 1969). This implies that if weather modification experiments were successful in below-normal or normal snowfall years, the capabilities of the highway department would be sufficient. However, if more snow was produced by cloud seeding during a winter of above-normal snowfall, there could be a shortage of equipment and a strain on personnel. Along with this efficiency problem, costs would be higher due to overtime pay and rental of equipment and services from private contractors.

If the results of the study done by the University of Colorado are reliable, then two conclusions can be made: (1) a 10% increase in snowfall from cloud seeding would not overtax the highway department during years of not greater than 135% of average snowfall, and cost increases would not be prohibitive; and (2) a 10% increase in snowfall in a far-above-normal year could force the highway department to spend a large amount of money to hire private contractors; this could result in a considerable loss of efficiency.

In the case of highway maintenance costs, good judgment is the key to success. Knowing the proper seeding time can reduce or eliminate any serious complications.

4. Recreational Opportunities

Recreational activities affected by weather modification in the Upper Colorado River Basin can be grouped by season: winter sports are sensitive to the condition of the snowpack; summer sports are centered around rivers, lakes, and reservoirs.

a. Winter Sports

By far the main outdoor sport in winter is

skiing. Skiing is widespread throughout the Basin, and since it was introduced into the High Alpine zones at Alta, Utah, in 1946, has blossomed into a multi-million dollar industry. Because it dwarfs other winter sports in economic importance, this discussion will deal only with skiing.

Unfortunately, very little quantitative information is available concerning the effects of increased snowpack upon the skiing industry. But four general observations can be made: cloud seeding would be advantageous in that (1) the skiing season would be lengthened, and (2) skiing conditions could be improved during the season. Cloud seeding could also be detrimental because (3) the threat to skiers from avalanches would be increased, and (4) accessibility of ski resorts for the skiers would be reduced.

A longer ski season would be the greatest advantage of a cloud seeding program. At least six inches of snow is needed for acceptable skiing conditions on most slopes (Langdale, 1968), and precipitation modification early or late in the season (for example, seeding early-season snow showers, producing six inches instead of three) could produce good skiing conditions that otherwise would not be present. In addition, if a general precipitation increase of 10% is accomplished over the winter months, the deeper, longer lasting snowpack would lengthen the season. Another advantage of cloud seeding is that additional snow during the season would improve skiing conditions on the base already present.

The chief disadvantage of increase precipitation for ski resorts would be the greater avalanche hazard (discussed earlier), which would force ski areas to close more often than they presently do. The greatest threat to skier safety would be during and immediately after storms from direct-action avalanches. In addition, avalanches may close highways leading to skiing areas. This problem of reduced accessibility is another

disadvantage of cloud seeding. Snowfall increase would make more work for highway crews, and if the increase was extreme, there might be a significant delay before the ski area could be opened (see highway maintenance section).

The problem of cloud seeding and skiing is a complicated one; when there is not enough snowpack for skiing or when fresh snow is needed to improve skiing, cloud seeding would probably be worthwhile; but when skiing conditions are good, extra snowfall could hinder skiing operations by causing avalanches and closing highways.

b. Summer Sports

The chief summer sports affected by precipitation modification are fishing, swimming, and boating. If cloud seeding resulted in more rainfall and less sunshine, these activities could be adversely affected. But besides this direct effect of cloud seeding, a potentially more harmful indirect effect could result. If could seeding were successful in increasing runoff, more storage area would be needed to contain this extra runoff; reliable runoff increases could result in more hydroelectric plants being built or in increased use of water for irrigation purposes. The best way to increase storage is by building dams to create reservoirs or to convert lakes into reservoirs. Dam-building may adversely affect recreational opportunities in the Upper Colorado River Basin in summer. The National Park Service commented on this problem in a survey of recreation in the Basin (U. S. Department of the Interior, 1950):

> "Reservoirs in high mountain country usually add little if anything to the general recreational value of the area and frequently destroy more than they create."

This reference to high mountain country certainly pertains to the Upper Colorado River Basin. It may seem that building a reservoir would create recreational opportunities by putting a body of water where none

previously existed, but reservoirs can "destroy more than they create" in several ways.

Probably the most destruction results from building a dam in naturally beautiful country which has remained relatively free from man's interference. Roads for transportation of men and machinery must be built; fill for the dam must be obtained, usually nearby; space for stockpiles and construction camps must be set aside; and tunnels and canals for transporting water must be cut through the land. The result is the destruction of a great deal of land valued by sportsmen and tourists, thereby tarnishing the chief economic support of many communities in the region.

Another problem connected with dam building is its effect on the quality of fishing. By controlling flow, dams can change the environment downstream. A dam near the headwaters does not affect the flow significantly and can enhance fishing downstream; but a dam anywhere else on the river will often destroy fishing. The National Park Service report stated (U. S. Department of the Interior, 1950):

> "In Colorado, ... existing fish production and extremely important attendant recreational values on various beautiful mountain streams would be jeopardized by the substitution of relatively barren reservoirs with bleak fluctuating shorelines."

Although dam building can result in deterioration of the surroundings, the new reservoirs do provide a new body of water for swimming and boating. And because its water temperature may be higher than that of the stream feeding it, the reservoir can be stocked with fish that thrive in the new environment. The reservoir becomes a center for summer recreational activities.

Cloud seeding does not result in any clear-cut advantage or disadvantage for summer recreational opportunities in the Basin, but it can be said that

weather modification should not be used as a tool for increasing recreational opportunities in summer. The possible detrimental effect on recreation should be taken into consideration if cloud seeding is to be used for other purposes.

5. Hydroelectric Power Plants

Hydroelectric power is well established in the Colorado River Basin today. There are 46 hydroelectric power plants with a combined capacity of three million kilowatts, 6.5% of the total United States capacity. In addition, 64 new sites are planned (U. S. Federal Power Commission, 1968).

One reason for this surge in development of hydroelectric power is that it does not consume fuel like other forms of power generation. Despite hydroelectric power's high initial expense (costing three times more to construct than a thermal plant), it is a relatively efficient and inexpensive means of power production. Once a dam is built, nature supplies the fuel to keep it in operation. Operating and maintenance costs in these facilities are one-half those of thermal power plants, and life expectancy is longer. Hydroelectric generation is also well adapted for peak-power demands because of its ability to start quickly and to make rapid changes in power output. As greater hydroelectric potential in the Basin is realized, the possible effects of weather modification on hydroelectric power must be explored.

Hydroelectric plants can be divided into two basic types: conventional and pumped storage. Conventional plants are those which exclusively use runoff to produce power. Pumped storage plants produce energy from water that has previously been pumped to an upper storage area. Such projects operate essentially as large storage batteries. Off-peak energy is used to pump water from a lower to an upper reservoir. The water is then stored and released through the plant for generation at peak-load times. A

hybrid also exists, a combined pump storage plant, which uses both pumped water and natural runoff for power generation.

This report will focus on conventional plants because they are the most sensitive to increases in runoff. Pumped-storage and hybrid types would require more storage space upstream, and could not rely merely on runoff increases to improve power production.

If an increase in precipitation causing increased runoff could be depended on through cloud seeding, there would be two benefits for hydroelectric facilities. First, efficiency could be increased. Water levels in reservoirs at the end of the dry season now must be maintained at a level high enough to provide reasonable assurance that these storage areas will be full at the end of the following wet season; if the engineers did not have to guard against the threat of insufficient rains following the dry season, water levels could be reduced, making more water available for immediate use during the season and making more storage space available for wet years.

Besides increasing efficiency, dependable runoff increases would also reduce costs for a hydroelectric plant. In years of below-normal flow, some of the power capacity may be idle; because demand remains high, the power utility must turn to some other source of power (usually thermal generation) which is much more expensive due to fuel costs. Increased runoff would reduce the chances of having flow low enough to idle plant capacity.

Cloud seeding is potentially of great benefit to hydroelectric plants. But it is important to determine the current reliability of cloud seeding.

Pacific Gas and Electric Company conducted a test program in California to investigate the feasibility of cloud seeding to increase runoff for hydroelectric plants over different types of watersheds (Eberly, 1965). They

found favorable cost-return ratios of between 1:4.6 and 1:14.1. The most economical type of watershed for cloud seeding was a large watershed with a high reservoir storage capacity and considerable elevation. Although they did not investigate the Upper Colorado River Basin, its characteristics resemble those of a watershed Pacific Gas and Electric classified as optimum for economic gain. On such a watershed, they estimated that merely a two percent increase in average annual runoff, if spread evenly throughout the year, should cover the total cost of a cloud seeding project.

Thus cloud seeding can produce some very significant and beneficial results in the area of hydroelectric power production at the present time, and increasingly so in the future as the hydrologic potential of the Basin is fully realized.

6. Water Utilization

Water is used for domestic, industrial, and municipal purposes in the Colorado Basin. These include irrigation, dilution of sewage and industrial wastes, livestock watering, hydroelectric power production, preservation of fish and wildlife, and recreation. Water is also exported for use in other basins.

The greatest potential benefits a cloud seeding program could have for water utilization are in the increase in runoff that might result. By far the major use of water is in irrigation. An increase in water supply from higher rainfall amounts would allow more land to be irrigated. The largest returns from this would come from the southern part of the Upper Basin, where there is some dry, fertile, unused land which could be made productive through irrigation. In the Alpine regions to the north, the increase in irrigable lands would not be as significant.

Along with the benefits derived from putting fertile land into use, more rainfall could also augment runoff during periods of low flow (that which is lower than

the flow exceeded 80% of the time). Some streams suitable for domestic use become unsuitable during periods of low flow due to a high concentration of dissolved solids. This is true on the Colorado at Cisco, Utah, and Lee's Ferry, Arizona; on the Green River at Green River, Utah, and on the San Juan River at Bluff, Utah (Iorns, et al., 1965).

Use of water during periods of low flow is also dangerous in livestock watering, and for irrigation when the sodium carbonate concentration is too high. In addition, on many smaller streams, low flow and high suspended sediment concentrations prevent recreational use of streams.

If more runoff was available during the dry season through cloud seeding, all these problems could be reduced or eliminated. This runoff increase is one of the greatest benefits of cloud seeding.

B. Legal Effects

1. Introduction

Because of uncertainties in the capabilities involved with weather modification, legal problems always arise. Complex questions such as "Who owns the weather?", "Who is liable for weather modification damages?", or "Are uniform state laws desirable?" are, as yet, unsolved. Modifiers may be faced with creating more problems than can be solved. While weather systems can be intentionally modified, these changes are looked upon both favorably and unfavorably. Consequently, 22 states now have statutes dealing with various aspects of weather modification. These state statutes are directed at (1) the body of rules governing the responsibilities and liabilities of weather modifiers (or to those who employ their services) and (2) regulation by government (most often by States) of weather modification activities (Taubenfeld, 1966).

The legal ramifications of modification activities are a result of either damages from severe local weather

conditions or from more subtle climatic changes. Historically, the public's concern and involvement over the effects of any modification have, on occasion, resulted in lawsuits. Liability is a far-reaching complication for weather modifiers, especially for those who represent private organizations. While state weather modification agencies are indemnified, no private organizations have been granted this privilege. Consequently, the few legal cases that have arisen over the years have not been comprehensive enough to warrant definitive answers on modification activities. What these cases have shown though, is that weather modifiers cannot divorce themselves from the variety of human responses that result from modification experiments.

Of greatest concern to any modification program is the problem of showing causal connection between the modification program and the resulting damage. If this can be established, legal compensation for this damage must be determined. However, problems envolve in assessing (1) the negligent party, (2) whether or not private operators are involved, or even (3) whether the damage claimed is a result of personal injury or of property damage. Whenever the damage claimed is that of property investments "the answer will turn on whether or not a person is held to have a property interest in a particular type of weather" (Taubenfeld, 1966). The right to cloud and weather ownership is involved here. Cases have been brought to court because of property interest, and the present legal decision must be broad-mined enough to protect the public as well as the modifiers. Until the scientists can be sure of the capabilities of such activities, the intricacies of lawsuits will not be sufficiently untangled; legal concepts may have to be altered from case to case in different parts of the country. It is quite apparent that causal relations between modification and damage or weather changes are not always easily seen.

2. Legal Doctrines to Date

The application of tort laws (pertaining to acts in which civil suits can be brought) to weather modification activities has received much attention. Certainly, the question, "Who owns the clouds?", is important here. More importantly, though, it is essential to (1) establish ownership of the water in the modified clouds and (2) determine water collection procedures. In seeking out the rules of capture related to cloud ownership, courts have based their decisions on previous legal cases, some failing to pertain directly to the situation. The Texas Gas-Oil case determined resource ownership when the natural resources were under an individual's land and were reasonably used. This ruling has since been related to clouds above the land; however, the transient nature of clouds confuses the issue, because gas and oil, although temporal resources, are available for use for a much longer time than clouds. Thus, a man owns the clouds when he reasonably uses them over his own property.

Some writers have related ownership of clouds to ownership of airspace. As in the Texas Gas and Oil ruling (1948), recent federal court decisions have held that the individual is restricted to that portion of the upper atmosphere that he can reasonable use in connection with the occupancy of his land. This new restriction did not have widespread acceptance with landowners since the original rule of law stated that landowners possessed upward into heaven and downward to perdition. In line with this, the only way in which the property owner could claim cloud ownership would be to make use of the clouds.

The nuisance theory, an addendum to the airspace rulings, has gained wide acceptance. "It (the nuisance theory) recognizes the ownership of the upper airspace and grants the remedy for nuisance when actual interference occurs. The landowner under this theory would have only

reasonable use of the clouds and is liable if his use created a nuisance to others" (Taubenfeld, 1966). However, the nuisance theory poses some interesting questions, especially those concerning weather modification from the ground and not necessarily from cloud seeding from above. The problem of smoke plume trajectories from ground smoke generators always has to be accounted for before modification attempts can be made. If a plume would happen to drift over another person's land and that person considered this a nuisance, the owner of the smoke generator would be liable of nuisance under this theory.

3. Conflicting Rulings

Unfortunately, issues conflict in legal rulings. The natural rights theory, a result of the ruling in the Southwest Weather Research Inc., vs. Jones case (327 S.W. 2n 417, 1959) holds that landowners have a "natural right" to cloud moisture content. Under the natural rights theory, landowners may do as they wish with the water from these clouds, which suggest that the landowner has riparian rights to the precipitation over his property (by riparian rights it is meant that a man may make "reasonable" use of the water that is transported past his property). By allowing landowners the right to use the cloud moisture above their property, these landowners may consequently by able to enjoy their land in its natural state.

In the Slutsky vs. City of New York case (97 N.Y.S., 2nd 238, 1950), it was cited that the landowner does not own the clouds overhead--a ruling that masks the meaning of the SW Weather Research Inc. case in which the landowner has the right to the moisture in the clouds. It would be consistent with this latter ruling "to find in the landowner a right to seed his own clouds (i.e., above his own land) for any purpose (so long, of course, as he didn't interfere with his neighbors right to peaceful surface use and atmospheric moisture)" (Davis, 1968).

4. A Specific Ruling In the Upper Colorado River Basin

One further doctrine exists in the Upper Colorado River Basin; an agreement commonly referred to as the Upper Colorado River Basin Compact. According to this compact, the landowners within the states of the Upper Colorado River Basin can appropriate the waters of the Colorado among themselves after they have provided the States of the lower Colorado Basin with their due share of the annual water supply (75,000,000 acre feet per ten years). In the Upper Colorado, the following States are apportioned the remaining waters of the Colorado River: Colorado (51.75%), Utah (23%), Wyoming (14%), New Mexico (11.25%), (National Academy of Sciences, 1968). Each state then distributes its water according to prior appropriation commencing with the oldest right in time to the youngest right, or until the water supply is exhausted.

5. Who Owns the Water?

We are not only concerned with cloud moisture ownership but also with the legal manner in which excess precipitation from cloud seeding is claimed and collected. The legal ramifications of increasing precipitation over a tract of land and recapturing the moisture at the surface is of utmost importance. These legal questions are germane if we are to determine the scope of weather modification effects on the hydrologic cycle, particularly on surface flow and groundwater flow. Although we may be able to cite rulings on cloud moisture ownership we must also establish precedents on water once it reaches the surface. Certainly this water, if misused, can easily alter the hydrologic cycle.

Water law texts advance many ideas on water ownership at the surface. The doctrine of foreign water (water moved from one watershed to another) raises problems on recapturing this moisture. In the case of Stevens vs. Oakdale Irrigation District (13 Cal 2n 343 351-2, 90 P.2d 58,

62-62, 1939) the courts granted an importer the right to recapture the water from his own watershed. A consequence of this may be that if a modifier triggers precipitation for beneficial use to landowners, and this water flows into natural stream channels, the modifier has the right to claim this water as his own. However, this consequence is a basis for the doctrine of developed water. If a modifier increases the water supply at the surface, the law supports the modifier's claim to this increase, even though the land on which the precipitation fell may be short of soil moisture. The problem with developed water lies in the manner in which the excess water is measured and recaptured, especially if it falls into stream channels.

One other doctrine that is used in the disposition of excess surface water from weather modification is the rule of reasonable use, a flexible policy which attempts to determine the rights of landowners and modifiers with respect to the surface waters; a landowner could make use of the clouds only if he were to use them reasonably. Accordingly, a landowner or modifier could use only the reasonable amount of water which would be of beneficial use to his land. This eliminates the possibility that a landowner or modifier could use an unreasonable amount of water for the benefit of his property. The term "reasonable beneficial use" is the key to this doctrine of reasonable use and has been defined in a California case as:

> "What is a beneficial use, of course, depends upon the facts and circumstances of each case. What may be a reasonable beneficial use, where water is present in excess of all needs, would not be a reasonable beneficial use in an area of great scarcity and great need. What is a beneficial use at one time may, because of changed conditions, become a waste of water at a later time" (Tulare Irrigation District vs. Lindsay-Strathmore Irrigation District; 3 Cal 2d 489, 567, 45 P. 2d 972, 1007).

Concerning weather modification, an increase in precipitation may be used reasonably and beneficially by the modifier or the hiring company as long as the modification activities do not violate the rights of other landowners. If the beneficial appropriative rights of others are violated, the courts will probably declare that activities of this type are not meeting the standards of appropriative reasonable usage.

6. Rights of Downwind Landowners and Water Users

We have confined most of this discussion to landowners and the moisture and clouds above their property. We should devote some time to the rights of the downwind landowners, since many of these landowners feel that they are being robbed of potential moisture, either in the precipitation form or through streamflow diversion. Assertions by modifiers that upwind modification seldom significantly increases the rain and snow processes is evading the question; the fractional atmospheric moisture loss from one watershed to the next is a real loss. Thus, the downwind landowners may find that they can bring suits against the modifiers, if indeed they are depriving these property owners of their fair share of moisture.

7. Conclusions

We have seen that weather modification is not an activity where legal problems can be dealt with lightly. For nearly every ruling handed down favoring modifiers' rights to the excess water, there seems to be a host of other rulings favoring the natural rights of landowners. The legal problems of weather modification must be thoroughly inspected before pursuing modification activities. The doctrine of prior rights in the West seems to be clouded by doctrine of private rights. These include results of the Slutsky case, the natural rights theory, the developed water ruling and the general nature of riparian rights. Rulings such as these have been used against weather modification activities.

Only if there is an understanding of past activities and the associated legal problems

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APPENDIX

FORTRAN PROGRAM
FOR ESTIMATING POTENTIAL EVAPOTRANSPIRATION

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      C   THIS PROGRAM ESTIMATES THE MONTHLY POTENTIAL EVAPOTRANSPIRATION
      C   OF AN AREA USING THE WEATHER BUREAU METHOD (MODIFIED PENMAN)
      C   FURTHER MODIFIED BY OUR OWN COEFFICIENT OF 0.56.
      C   GRAPHICAL REPRESENTATIONS ARE REDUCED TO MATHEMATICAL EXPRESSIONS
      C   ADAPTABLE TO COMPUTER USE BY LAMOREUX (1962)
      C   INPUT PARAMETERS ARE MEAN MONTHLY AIR TEMPERATURE IN DEGREES F,
      C   MEAN MONTHLY DEW POINT TEMPERATURE IN DEGREES F, AVERAGE WIND SPEED
      C   FOR THE MONTH IN MILES PER DAY AND AVERAGE SOLAR RADIATION IN
      C   LANGLEY'S PER DAY, AND THE NUMBER OF DAYS IN THE MONTH.  THE
      C   OUTPUT IS POTENTIAL EVAPOTRANSPIRATION FOR THE MONTH IN INCHES.  THE
      C   FIRST DATA CARD SHOULD CONTAIN AN INTEGER--THE NUMBER OF CARDS
      C   TO FOLLOW.  FOLLOWING DATA CARDS SHOULD HAVE THE
      C   INPUT PARAMETERS IN THE ORDER MENTIONED, EACH ONE SEPARATED
      C   BY BLANKS.
    1       IMPLICIT REAL (A-L,O-Z)
    2       READ,N
    3       DO 1000 M = 1,N
    4       READ,AIRTMP,DEWTMP,WNDSPD,SOLRAD,DAYS
      C     ESMEA IS THE VAPOR PRESSURE DEFICIT WHEN AIRTMP IS GREATER
      C     THAN OR EQUAL TO THE DEWTMP WHICH IS GREATER THAN OR
      C     EQUAL TO -16 DEGREES F
    5       ESMEA=(.0041*AIRTMP+.676)**8-(.0041*DEWTMP+.676)**8-.000019*
           1(AIRTMP-DEWTMP)
    6       ANUMER=EXP((AIRTMP-212.0)*(.1024-.01066*ALOG(SOLRAD)))-.0001
           1+.0105*ESMEA**.88*(.37+.0041*WNDSPD)
    7       DENOM=.04686*(.0041*AIRTMP+.676)**7+.01497
    8       LKEVAP=ANUMER/DENOM*DAYS*.56
    9       PRINT 250,AIRTMP,DEWTMP,WNDSPD,SOLRAD
   10  250  FORMAT ('0','AIRTMP=',F5.1,'     DEWTMP=',F5.1,"     WNDSPD=',
           1F6.1,'     SOLRAD=',F6.1)
   11       PRINT 500,LKEVAP
   12  500  FORMAT ('0',T20,'ESTIMATED POTENTIAL EVAPOTRANSPIRATION FOR MONTH=
           1',F4.1'     INCHES')
   13 1000  CONTINUE
   14       STOP
   15       END
```

TABLE D

INPUT PARAMETERS			AREA #1		ESTIMATED POTENTIAL EVAPOTRANSPIRATION FOR THE MONTH IN INCHES	
Month	Avg Daily Air Temp For Month (°F)	Avg Daily Dew Pt Temp For Month (°F)	Avg Wind Spd For Month (mi/day)	Avg Sol Radiation For Month (ly/day)	Weather Bureau Method	With Coefficient of .56
JAN	19.7	5.0	144.0	212	1.2	.7
FEB	23.0	5.0	168.0	313	1.7	1.0
MAR	29.0	10.0	216.0	423	3.1	1.7
APR	39.5	15.0	240.0	512	4.9	2.8
MAY	47.9	18.0	264.0	552	6.9	3.9
JUNE	55.7	25.0	264.0	632	8.3	4.7
JULY	61.8	30.0	240.0	600	8.6	4.8
AUG	60.3	30.0	216.0	505	7.1	3.9
SEPT	54.0	25.0	240.0	476	6.2	3.5
OCT	43.8	20.0	216.0	361	4.1	2.3
NOV	29.9	10.0	168.0	234	2.0	1.1
DEC	22.2	5.0	144.0	184	1.3	.7
			ESTIMATED AVERAGE YEARLY TOTAL		55.4	31.1

TABLE E

INPUT PARAMETERS			AREA #2		ESTIMATED POTENTIAL EVAPOTRANSPIRATION FOR THE MONTH IN INCHES	
Month	Avg Daily Air Temp For Month (°F)	Avg Daily Dew Pt Temp For Month (°F)	Avg Wind Spd For Month (mi/day)	Avg Sol Radiation For Month (ly/day)	Weather Bureau Method	With Coefficient of .56
JAN	25.1	12.0	144	227	1.3	.7
FEB	30.0	12.0	168	324	2.1	1.2
MAR	37.2	15.0	216	434	4.0	2.2
APR	46.6	20.0	240	546	6.0	3.4
MAY	55.1	22.0	264	615	8.5	4.8
JUNE	63.7	30.0	264	708	10.2	5.7
JULY	70.7	35.0	240	676	10.7	6.0
AUG	68.2	40.0	216	595	8.6	4.8
SEPT	61.0	30.0	240	514	7.3	4.1
OCT	50.0	25.0	216	373	4.7	2.6
NOV	38.3	20.0	168	260	2.4	1.3
DEC	28.3	12.0	144	212	1.6	.9
			ESTIMATED AVERAGE YEARLY TOTAL		67.4	37.7

TABLE F

INPUT PARAMETERS AREA #3

Month	Avg Daily Air Temp For Month (°F)	Avg Daily Dew Pt Temp For Month (°F)	Avg Wind Spd For Month (mi/day)	Avg Sol Radiation For Month (ly/day)	ESTIMATED POTENTIAL EVAPOTRANSPIRATION FOR THE MONTH IN INCHES: Weather Bureau Method	With Coefficient of .56
JAN	24.0	12.0	144	227	1.2	.7
FEB	30.8	12.0	168	324	2.1	1.2
MAR	40.5	15.0	216	434	4.4	2.5
APR	51.0	20.0	240	546	6.7	3.8
MAY	60.2	22.0	264	615	9.4	5.2
JUNE	68.8	30.0	264	708	11.1	6.2
JULY	75.7	35.0	240	676	11.5	6.5
AUG	73.4	40.0	216	595	9.5	5.3
SEPT	64.9	30.0	240	514	7.9	4.4
OCT	52.5	25.0	216	373	5.1	2.8
NOV	37.0	20.0	168	260	2.2	1.2
DEC	27.9	12.0	144	212	1.5	.9
		ESTIMATED AVERAGE YEARLY TOTAL			72.6	40.7