Denver Journal of International Law & Policy

Volume 6
Number 3 *Special Issue*
Water Needs for the Future

Article 27

May 2020

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I. INTRODUCTION

The management and use of existing and potential water supplies is a topic of critical importance. As the demands for the available supplies increase, the problems of water allocation and distribution will increase, and hard decisions on optimal societal utilization will be needed. An increasingly high premium must be placed on the management of the *total* water resource: surface water, underground water, and atmospheric water. If additions are to be made to the total volume of water supplies to land areas over the globe, the additional water must, as does natural precipitation, come from the atmosphere. Diversion and transfers can redistribute surface water but do not increase the initial supply. The atmosphere, in addition to being the initial source for surface water, also constitutes the primary "sink" to which this water is lost.

How Much Water is There in the Atmosphere?

Huge quantities of water vapor pass over the watersheds of the semiarid Western United States. However, not more than about one percent of the water vapor present in the air that passes over Colorado annually, for example, is condensed into clouds that can form precipitation. Most of the atmospheric water remains in vapor form and is not potentially available for precipitation. There are extensive periods, however, when the local atmosphere is saturated and some of the water vapor condenses into liquid drops or ice particles forming clouds. Some of this water is in a suitable state for precipitation and is the water from which all natural precipitation comes. Only a portion of this condensed cloud water actually reaches the ground as precipitation.

The type of cloud in which condensed water is contained is important in considering how much of the cloud water reaches the ground as precipitation. Orographic clouds are

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formed when air is forced over a mountain. Orographic clouds are relatively simple and therefore their physical descriptions are relatively complete and accurate. Cumulus clouds are usually associated with summertime weather phenomena. Cumulus clouds can be small, white, puffy clouds typical of many warm summer days, or they can be large storms, sometimes resulting in lightning, hail, and heavy rains. A small fraction of the summertime cumulus clouds in Colorado are highly efficient in converting condensed cloud water into drops or ice particles large enough to fall out and reach the ground. Many others, however, are not. Most summertime thunderstorms of the High Plains region of the United States probably precipitate 5 to 20 percent of the cloud water, while the remaining portion reevaporates as the clouds move out of their source area and into a drier region. A few summertime cumulus clouds are highly efficient precipitators and convert 70 to 80 percent of the cloud water into precipitation. Still other cumulus clouds have zero efficiency, and none of the cloud water is precipitated.

Some orographic clouds are also highly efficient in converting cloud water to rain or snow while others are highly inefficient. Overall, the natural precipitation efficiency of orographic clouds in wintertime may be higher than for summertime cumulus clouds. It is the water that condenses to form clouds but does not reach the ground as precipitation that constitutes the potential for weather modification to augment precipitation. Under some conditions, this potential is large since in these cases conditions are suitable for the formation of additional precipitation by enhancing cloud efficiency through cloud seeding. Under many other conditions, the natural inefficiencies are inherent in the system and cloud seeding cannot be an aid.

The amount of atmospheric water vapor and the existing weather conditions are also important in the rate of depletion of existing surface and underground water supplies. Some 90 to 95 percent of the average annual precipitation over Colorado is returned to the atmosphere by evaporation and evapotranspiration while the other 5 to 10 percent is transported out of the state in the form of runoff. A major portion of the water transfered back to the atmosphere is in the form of useful transpiration or unavoidable evaporation losses. An important portion of it, however, might be conserved or utilized more effectively by employing good management practices.

This paper briefly considers the potential of weather modification as a technology for increasing usable water resources. It considers both the augmentation of water supplies by enhancing the efficiency of cloud water conversion to precipitation and the conservation of water by modifying evaporation and evapotranspiration losses.

II. CLOUD AND PRECIPITATION MODIFICATION

Clouds and weather can clearly be modified under some circumstances. However, given differing weather conditions, one could either cause more efficient use of cloud water and produce more precipitation, produce no change in cloud efficiency or precipitation, or even decrease the natural precipitation efficiency of the cloud and thereby possibly reduce the precipitation on the ground. Clearly one must be able to define and recognize just which effect will occur before practical operational weather modification efforts can be undertaken. The important point is that there are many situations when the natural precipitating efficiency is low and can be increased by treatment. Since summertime cumulus cloud systems are very complex and the technology for their modification is very primitive, we will only briefly summarize their potential for modification. Precipitation augmentation prospects for the simpler and better defined wintertime orographic clouds will be discussed in greater detail.

A. *Summertime Cumulus Cloud Systems*

While changes in both the clouds and precipitation have been shown from seeding certain individual convective summertime clouds, the augmentation of precipitation over an area has not been demonstrated with a satisfactory degree of certainty for most geographical regions. The results from at least four carefully conducted experiments suggest (but not at a statistically significant level) a decrease in precipitation following seeding. At least two or more recent experiments using more advanced concepts provide results indicating precipitation increases, but still without a substantially high degree of certainty.

These cloud types are complex, very short-lived, and difficult to study. A probable reason for present conflicting evidence is that differing effects resulting in both precipitation increase and decrease are incorporated in existing experimental samples. Clearly, cloud conditions and seeding methods leading to precipitation increases or precipitation decreases must be defined before extensive operational field programs are feasible. The Bureau of Reclamation in its large High Plains precipitation augmentation research experiment, and other groups, such as the South Park Area Cumulus Experiment (SPACE) at Colorado State University, are addressing these problems with the parallel and complimentary efforts of laboratory simulations, field cloud studies, and field seeding experiments. The benefits can be large, particularly in the semiarid, Western United States.

B. *Wintertime Snowpack Augmentation*

The basis for considering augmentation of snowfall from wintertime orographic clouds is considerably more advanced than summertime cumulus precipitation augmentation, and the basic technology for augmenting precipitation in many geographical areas on a determinate basis now exists. Careful research over a 15-year period has provided the basis for defining which clouds are efficient and which ones require treatment to improve their efficiency. These concepts have been confirmed in carefully designed, long term field experiments.

During two randomized seeding experiments carried out by Colorado State University, an average of less than half of the cloud water was converted to precipitation reaching the ground on unseeded days defined as having naturally inefficient cloud water utilization. On similarly defined days that were seeded, actual precipitation averaged nearly twice as much as on the unseeded days. These results, of course, apply only to certain weather situations, and in the Northern Colorado Rockies these days constitute only about 15 to 30 percent of the cloudy days. On the other 70 to 85 percent of the days, the natural precipitation process was efficient so that no seeding effects should have been expected, and none were observed. The large increases on certain days, however, can be shown to have the potential for augmenting overall snowfall in most Colorado mountain areas by 10 to 20 percent over a winter season. Results of another six-year field test by Colorado State

University in the Wolf Creek Pass area of southern Colorado indicated even larger percentage increases since there was a higher frequency of warmer, more seedable weather episodes. A subsequent randomized experiment in this same area by the Bureau of Reclamation provided confirmation and refinement of the physical concepts but demonstrated the difficulties involved in trying to predict the seedability of the respective cloud systems for 24 to 30 hours in advance. In fully operational programs with automated data observation systems, seeding operations can and should be based primarily on current observations rather than forecasts.

Streamflow from snowpack increases should be at least comparable to corresponding natural increases in snowfall in various watersheds. The Colorado State University Wolf Creek Pass experiment provided strong, statistically significant evidence of a streamflow increase of about 23 percent during the continuously seeded winter seasons.[1] This amounted to a total of 276,000 acre-feet of water, of which half was produced in the head waters of the San Juan River Basin and the other half in the Rio Grande. Based on the changes in precipitation determined to be feasible and the results of this Wolf Creek Pass streamflow analysis, the potential for water augmentation from Colorado watersheds should be of the order of 1.5 to 2.0 million acre-feet per year.

C. *Societal and Environmental Impacts of Augmented Precipitation*

Augmenting water resources in the Western United States can make a substantial contribution to the solution of current regional and national water resources problems. The direct cost of the augmentation would be low in relation to present water values and particularly those to be expected in the future. Weather modification affects entire communities or regions, not just individuals or individual groups. Thus, the entire spectrum of societal and environmental impacts must be considered.

First, studies to date have not identified any short term

1. Mielke, Williams & Wu, Covariance Analysis Technique Based on Bivariate Log-Normal Distribution with Weather Modification Applications (1977) (to be published in 16 J. APPLIED METEOROLOGY).

environmental impacts that are of a magnitude that would preclude the use of weather modification for augmenting mountain snowpack.[2] Most of the undesirable effects that might occur can be managed. For example, treatment can be terminated during particularly bad storms or heavy snow years. It also appears that most adverse environmental impacts that might arise are reversible by subsequently terminating the augmentation treatment.

Second, as in naturally occurring heavier snow years, augmented precipitation will cause added expenses at the locale where precipitation is being augmented. It seems likely that expenses incurred could be borne as part of the cost of the added water without seriously affecting the cost-effectiveness of the technology. A method for distribution of the direct costs, benefits, and reimbursements does present a difficult problem that will have to be addressed.

Third, water ownership and cost sharing for its production will have to be established.

Fourth, special societal problems are introduced by increasing water in western watersheds[3] since the relatively small community affected by the additional snowfall has little or no use for the additional water while the relatively large user community, frequently hundreds of miles downstream, is the beneficiary. At least some, and likely many, of the affected communities may object to this arrangement even though they, by choice, live in the water source area of many downstream agricultural, urban, and industrial water users. Land use issues are raised. Perhaps the greatest present and potential land use value for these mountain watersheds is for the production and storage of usable water supplies. This may or may not be compatible with present recreation, mining, and agricultural uses. Expanded working relationships will have to be developed to facilitate multipurpose land use planning and implementation.

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2. STANFORD RESEARCH INSTITUTE, THE IMPACTS OF SNOW ENHANCEMENT: A TECHNOLOGY ASSESSMENT OF WINTER OROGRAPHIC SNOWPACK AUGMENTATION IN THE UPPER COLORADO RIVER BASIN (1974).

3. B. Farhar, Weather Modification in the United States: A Socio-Political Analysis, 1975 (Ph.D. Thesis, University of Colorado).

III. MANAGEMENT TO REDUCE UNPRODUCTIVE EVAPOTRANSPIRATION

The reduction of water returned to the atmosphere through evaporation, sublimation, and transpiration at the surface-atmosphere interface has a high potential for enhancing water supplies in the Western United States.

A. *Low Precipitation Agricultural Areas*

In agriculture on semiarid lands, water conservation techniques are aimed at maintaining limited subsoil moisture supplies by reducing evapotranspiration. One conservation technique involves keeping soil free of vegetation for a growing season to reduce evapotranspiration and to allow the precipitation which occurs that year to replenish subsoil moisture. This moisture is then used to enhance the water supply for the crops which are planted the following season. A second widely-used agricultural technique, mulching, involves only partially removing crop stubble after the crop has been harvested. The plant stems are left standing to intercept blowing snow during the winter. If the snow had not been trapped it probably would have sublimed and returned to the atmosphere. Thus, in the first example, evapotranspiration is reduced, and, in the second, sublimation losses from blowing snow are reduced. A number of additional techniques are routinely used in agriculture aimed primarily at reducing evapotranspiration losses.

B. *Low Precipitation Range Area*

Ranchers in semiarid areas conserve moisture for productive vegatative growth by reducing nonproductive evapotranspiration losses.[4] This is accomplished by controlling vegetation types on rangeland. One example of this type of control is reduction of big sagebrush. The moisture which would normally be used by the sagebrush can then be used by plants which are better food producers for grazing animals. In addition, Sturges has estimated that reducing big sagebrush foliage[5] on rangeland can result in up to a 15 percent increase in water yield under the most favorable conditions.

4. D. Sturges, Hydraulic Relations on Undisturbed and Converted Big Sagebrush Lands: The Status of our Knowledge, Mar. 1975 (U.S.D.A. Forest Service Research Paper RM-140).
5. *Id.*

C. *Alpine Areas*

In addition to water savings resulting from management of agricultural and rangelands, the management of watersheds in the West has a high potential for enhancing streamflow. Mountain watersheds often have a region above timberline which is typically referred to as the alpine region. Estimates of the alpine area coverage in Colorado range from 1.9 to 4.5 million acres, which corresponds to approximately 3.5 percent of the surface area of the state. The runoff resulting from this relatively small area produces about 20 percent of Colorado's total water yield. The amount of water returned to the atmosphere from this region by evaporative losses as a whole has not been well-defined. A major portion of these losses are probably due to sublimation of windblown snow. Santeford defined water losses due to sublimation on a mountain ridge line at 62 percent of the total wintertime precipitation for the area.[6] Twenty percent of this amount was due to direct sublimation from the snow surface, and 60 percent was due to losses related to blowing snow. This study and a subsequent study[7] investigated snow entrapment by inducing avalanches on the lee slopes of the ridge. The Santeford study indicated that approximately half of the windblown snow losses in his study plot could be saved using this technique. Such savings would produce an increased water yield of 270 acre-feet of water per mile of treatable ridge line. Other studies in the alpine region have investigated the possibility of enhancing runoff and changing the timing of runoff through the interception of blowing snow by snowfences.[8] Terrain modification is another technique which is aimed at reducing sublimation losses resulting from blowing snow. Estimates of water savings from these techniques are not well-defined. It should be recognized that treatment of the relatively small alpine area may result in significant streamflow increases.

D. *Subalpine Areas*

In the high elevation, forested regions (often referred to as

6. H. Santeford, Management of Windblown Alpine Snows, 1972 (unpublished Ph.D. Thesis, Colorado State University).

7. M. Pope, Snow Surface Modification in the Alpine to Augment Water Yield, 1977 (unpublished M.S. Thesis, Colorado State University).

8. M. Martinelli, Water Yield Improvement from Alpine Areas: The Status of our Knowledge, Mar. 1975 (U.S.D.A. Forest Service Research Paper RM-138).

subalpine) watershed management techniques can enhance streamflow significantly. The Colorado River Basin has a total alpine and subalpine areal coverage above about 9000 ft.msl (2900 m) which is 17 percent of the basin area, yet this portion of the basin is responsible for 80 percent of the streamflow. Thirty years of study have shown that the subalpine region is capable of producing 25 percent more streamflow if 40 percent of the watershed area is occupied by small, protected openings. This study by the National Forest Service in the Fraser National Experimental Forest indicates that the openings should be 5 to 8 tree-heights in diameter and 5 to 8 tree-heights apart.[9] The pattern results in a redistribution of snow with more snow in the openings and less snow in the trees. The net effect is that the snow melts earlier in the spring and, due to reduced evapotranspiration, streamflow is increased. The increased streamflow remains stable at approximately a 25 percent increase for 30 years with lesser increases evident for up to 60 years. The increased runoff is a by-product of timber harvest. It should be emphasized, however, that only when the harvest is appropriately planned and managed will increases in streamflow result. This technique is silviculturally sound, does not degrade water quality, and, if planned to fit the terrain, is not aesthetically displeasing. Watersheds with commercial forests to which this type of treatment might be applied comprise about ten million acres in Colorado alone.[10] Leaf and Alexander have numerically simulated a forest management technique which considered optimal forest growth and watershed runoff enhancement for the South Tongue River of the Bighorn National Forest in Wyoming.[11] The simulation was run for a 120-year time period with a stepwise harvesting and rejuvenation of the watershed. The simulated treatment resulted in increased streamflow ranging from 10 to 20 percent for the entire period. This method pro-

9. C. Leaf, Watershed Management in the Central and Southern Rocky Mountains: A Summary of the Status of our Knowledge by Vegetation Types, Mar. 1975 (U.S.D.A. Forest Service Research Paper RM-142).

10. R. Alexander, Silviculture of Central and Southern Rocky Mountain Forests: A Summary of the Status of our Knowledge by Timber Types, Apr. 1974 (U.S.D.A. Forest Service Research Paper RM-120).

11. C. Leaf & R. Alexander, Simulating Timber Yields and Hydraulic Impacts Resulting from Timber Harvest on Subalpine Watersheds, Feb. 1975 (U.S.D.A. Forest Service Research Paper RM-133).

vides a very lucrative potential for enhancing streamflows in the West.

E. *Streambeds and Standing Water Areas*

Rivers of the West are bounded by phreatophytes (Greek word meaning "well plants"). These plants use the water that flows in the streams and, through evapotranspiration, release the water to the air. It is estimated that phreatophytes occupy 16 million acres along streams in the 17 Western States.[12] Horton and Campbell have estimated that one to two acre-feet of water per acre of phreatophyte can be saved each year by removing the phreaophytes.[13] If only 25 percent of the phreatophyte area were treated, this translates into 4 to 8 million acre-feet of additional streamflow per year in the 17 Western States.

F. *Environmental and Social Impacts of Water Conservation Treatment*

Establishment of optimum multiple-use management techniques for mountain watersheds and phreatophyte areas often requires a compromise between the environmental factors and the needs of society. Seldom are areas best managed by devoting the land to a single use. Most of the environmental difficulties associated with these techniques are or can be defined. Intelligent decisions cannot be made on the use of watershed management techniques unless the environmental ramifications are carefully considered.

Social and legal difficulties associated with water ownership, treatment cost, and compensation for those receiving disbenefits must also be resolved for optimal technique utilization to occur.

IV. SUMMARY AND CONCLUSIONS

The atmosphere under some meteorological conditions is a source for additional surface and subsurface waters. The atmosphere is also a sink for evaporative losses under other conditions. By utilizing well-defined techniques for augmenting wintertime orographic precipitation, it is possible to increase

12. SELECT COMMITTEE ON NATIONAL WATER RESOURCES, 86TH CONG., 2D SESS., WATER RESOURCES ACTIVITIES IN THE UNITED STATES: EVAPO-TRANSPIRATION REDUCTION (Comm. Print 1960).

13. J. Horton & C. Campbell, Management of Phreatophyte and Riparian Vegatation for Maximum Multiple Use Values, Apr. 1974 (U.S.D.A. Forest Service Research Paper RM-117).

the atmospheric source. Management of watersheds provides a means for reducing evaporation and evapotranspiration losses, thus reducing the atmospheric sink for moisture. Combined, these treatments constitute potential major water supplies to assist in meeting the water needs of the future for Colorado, the United States, and the world.

Specifically, weather modification for augmenting orographic precipitation over many western watersheds, using existing or near-ready techniques has the potential of adding 10 to 20 percent to natural supplies. In Colorado, this can involve the addition of up to 1.5 to 2.0 million acre-feet of water annually. The increase in available water supplies from management practices to reduce unproductive evaporative losses are comparable and likely greater. In addition, a synergistic relationship has been suggested for these two techniques.[14]

Each of these resource utilization techniques involves societal and environmental impacts that must be addressed. The total water resources, including the atmospheric component and the impacts of its utilization, must be included in water planning for the future.

14. A. Rango, Possible Effects of Precipitation Modification on Selected Watershed Parameters, 1969 (unpublished Ph.D. Thesis, Colorado State University).