POTENTIAL WATER AUGMENTATION FROM CLOUD SEEDING IN THE COLORADO RIVER BASIN

Steven M. Hunter
Technical Service Center
Bureau of Reclamation
Denver, CO 80225

Abstract. A spatially-distributed snow energy and mass balance model, updated with all available snowpack observations, is used to assess the potential for water augmentation by winter orographic cloud seeding in the Colorado River Basin. The modeling system outputs snow water equivalent (SWE) on a 1 km grid throughout the continental United States. The April 1 SWE from the last two years are horizontally integrated across existing and potential seeding target areas in the basin and multiplied by approximately 0.1 to calculate water yields from an assumed seeding-induced increase of 10 percent. Major uncertainties in this method, including snowpack ablation and target area selection, are described. Given those uncertainties, it is estimated that in an average precipitation year, about one million acre-feet of additional snowpack water could be produced by seeding. Somewhat more could be produced in a wet year and about 500,000 acre-feet in a dry year. These figures are reasonably close to those from older studies of augmentation potential in the basin.

1. BACKGROUND

Seeding of orographic (mountain) clouds in the cool season has been done in the Upper and Lower Colorado River Basin since the 1960s, on an operational and research basis. Several studies have been done in that time to estimate the potential water augmentation from seeding in the basin. The following are some of the older such studies and their estimates of water yield, as cited in a Bureau of Reclamation report (Water and Power Resources Service 1980):

Table 1. Previous water yield estimates from cloud seeding in the Colorado River Basin

Source	**Dates**	**Water Yield Estimates (Acre-ft)**
Bureau of Reclamation (Grant 1969)	1967-1968	1,870,000
Stanford Research Institute (Weisbecker 1974)	1971-1972	1,150,000*
North American Weather Consultants, Twelve Basin Investigation (Elliott et al. 1973)	1972-1973	1,315,000 (liberal)† 903,000 (conservative)†

* Figure from this document is halved because it assumed a 20% increase, whereas today the often accepted increase is 10%

† Figures from this study do not include estimates from the Gila River Basin in Arizona, which is in the lower basin and most of which is below 9,000 feet elevation.

These figures are for seeding *all* target areas in the basin, with areas selected based on the differing criteria of each study. Since these studies are over 30 years old, it was desired to update them with more recent information. Also, motivation was added by the letter of 25 August 2005 from the seven Colorado Basin states to Interior Secretary Norton. This letter requested a long-term plan for operating Lakes Powell and Mead during hydrologic drought, and included a recommendation that Reclamation develop a plan for water augmentation through cloud seeding. Also, the funding and context for the current work were provided by the Colorado Water Conservation Board's (CWCB) "Winter Storm Climatology" study, of which Reclamation had a part.

2. AUGMENTATION ESTIMATION PROCEDURES

We assumed a 10% increase in April 1 snow water equivalent (SWE) in existing and potential target areas, with SWE provided by the Snow Data Assimilation System (SNODAS; Carroll et al. 2001). The SNODAS consists of a spatially-distributed snow energy and mass balance model, updated with all available snow water equivalent, snow depth, and snow cover (from surface, aircraft, radar, satellite) data. Model outputs include SWE, snow depth, snowmelt, pack temperature, and sublimation. Daily and historical model output for the state of Colorado may be found online (Hunter 2004). The output has been available nationwide since October 2003, and for some areas before that date. Therefore data exist for two winters only, a short climatological record compared to the more traditional Snow Telemetry (SNOTEL) and snow course datasets. Unlike these datasets, however, SNODAS provides spatially continuous data at 1 km resolution. The model has been validated (Cline et al. 2004) in the Colorado Mountains against the Corps of Engineers widely-validated SNTHERM model.

2.1 Determination of Target Areas

A major variable in estimating water yield from seeding will be selection of the seeding target areas. We split this task into two sections: *existing* areas already being seeded by operational programs (in Utah and Colorado only), and *potential* new areas. Geographic Information Systems (GIS) maps were obtained for the former. Selection criteria for existing areas vary, but are in general elevation-based. In Utah, this criterion is 7000 feet or higher, whereas in Colorado it is above 8000-9000 feet. These criteria were informally adopted and reflect the higher elevations in Colorado. In any event, the existing areas were used as provided, with no modification except to exclude parts outside the Colorado River drainage area. The existing target areas are listed in Table 2.

Table 2. Existing Target Areas

Colorado	Utah
1. Upper Arkansas†	11. Fishlake Mtns.†
2. Gunnison North	12. Boulder Mtn. †
3. Gunnison South	13. Uinta Mtns. South
4. Vail	14. Dixie Natl. Forest†
5. Beaver Creek	
6. Grand Mesa North	
7. Grand Mesa South	
8. San Miguel Mtns.	
9. Western San Juans	
10. Eastern San Juans	

† Portion of area outside Colorado River Basin

For *potential* areas, a strict 9000 foot base threshold was used as a criterion in the Colorado basin regions of Arizona, New Mexico Colorado, Utah, and Wyoming. This criterion follows that specified in a planning document for a winter cloud seeding research project called the Colorado River Snowpack Enhancement Test (CREST; Super et al. 1993). Further criteria from this document were that the candidate region usually has at least 20 km west-east extent of 9000 feet elevation area and that it is largely or wholly outside designated wilderness areas. These criteria were used to select proposed areas for cloud seeding *experimentation*, whereas this document is concerned with all potential target areas for *operational* seeding. It would be impractical to conduct experimentation within a wilderness area, since key instrumentation would not be allowed. Some operational projects target wilderness areas, although their seeding generators are located outside the boundaries of those areas. So for the present study, several additional areas, including those with wilderness designations and barriers no wider than 5 km, have been added. Finally, the potential new areas were included only if they are outside existing target areas.

The CREST locations were given spatial extents through use of GIS software, since the planning document gave only general text descriptions of locations (the authors had to manually search 1:1,000,000 aeronautical charts). Based on the slightly different criteria (stated above) and more sensitive mapping with GIS software, we identified five additional potential target areas (Table 3). The Bureau of Reclamation report (Water and Power Resources Service 1980) identified the entire Mogollon Rim in Arizona as a potential target, whereas we exclude all of it (except for the San Francisco Mountains) because it is largely below 9000 feet elevation. The snowfall at such low elevations, particularly if they are at southerly latitudes as in Arizona, would frequently occur at relatively warm subfreezing temperatures, during which silver iodide would be ineffective. Seeding by liquid propane gas expansion, which can create ice crystals at warmer temperatures (thresholds -1°C vs -5°C for silver iodide), might be a viable alternative for such locales.

An essential point is that, despite the CREST criteria application, there is still substantial subjectivity in selecting any seeding target area. All new potential areas are listed in Table 3. Both existing and potential areas are shown by the map in Fig. 1.

Table 3. Potential Target Areas

Colorado	Utah	Wyoming	Arizona
15. Park Range	20. Uinta Mtns. North	24. Wyoming Range	26. Kaibab N.F.[#]
16. Elkhead Mts.	21. La Sal Mts.	25. Wind River Mtns. West[#]	27. Chuska Mts. AZ/NM)
17. White R. Plateau	22. Mt. Ellen[#]		28. White Mts.
18. Uncompahgre Plateau	23. Abajo Pk. [#]		29. San Francisco Peaks[#]
19. Central Rockies[@]			

[#] Areas not identified in CREST document

[@] Area was operationally seeded in previous years by Denver Water utility

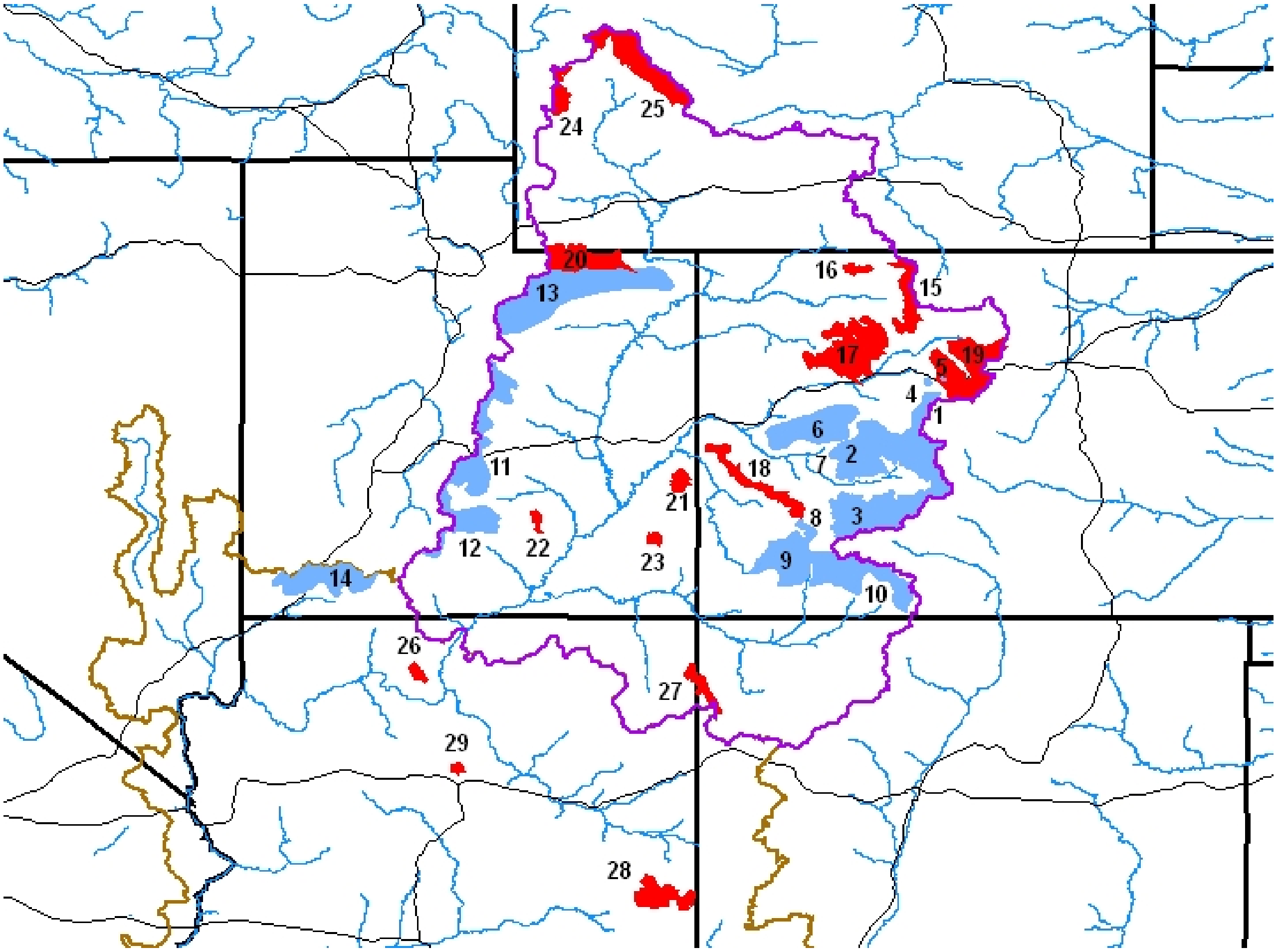

Figure 1. Existing (operational) cloud seeding target areas (blue) and potential target areas (red). Areas are indexed with numbers corresponding to those in Tables 2 and 3, respectively. Purple and brown polygons are Upper and Lower Colorado River basin outlines, respectively.

2.2 Nature of Calculations

For the current application, we integrated SNODAS 1 km SWE data over seeding target areas at the traditional end of the mountain snow accumulation season, April 1 (also the traditional beginning of the snowmelt runoff season). To estimate water volumes produced by seeding in *potential* areas, these integrations are divided by ten, since there is statistical, physical and modeling evidence for about 10 percent augmentation of natural precipitation (snowfall) by orographic cloud seeding (American Meteorological Society 1998). Physical cause-and-effect relationships have yet to be fully demonstrated, however. Since seeding has been conducted in *existing* areas, it is assumed that SNODAS SWE already reflects the 10% increase, or 110% of natural snowpack. Therefore the integrated SWE is divided by 11 in these areas. These calculations were made for both 2004 and 2005 April 1 SWE data. The year 2004 was an unusually dry one in the Upper Basin and 2005 was a relatively wet one. See Fig. 2 for a graphical representation of the precipitation in the basin.

That the calculations are based on “snapshots” of the snowpack on April 1 requires a caveat. They are representative of cloud seeding augmentation of snowfall to the extent that the snowpack has continually increased and melted little over the preceding winter. Such would not be the case in relatively warm southerly and/or low elevation mountains, as in Arizona. Because some melt occurs even in colder climates and/or higher elevations, the April 1 SNODAS SWE will be lower than SWE from accumulated seasonal *snowfall*. The latter is actually the more appropriate variable for augmentation potential, but is only measured at a few points. Therefore the seeding-generated 10% increases of the April 1 SNODAS SWE, as presented below, might be expected to *underestimate* in proportion to seasonal snowpack ablation (melt, sublimation [ice to vapor] or evaporation). Snowfall measurements from gauges have significant errors as well. Moreover, some of the gauged precipitation could have fallen as rain.

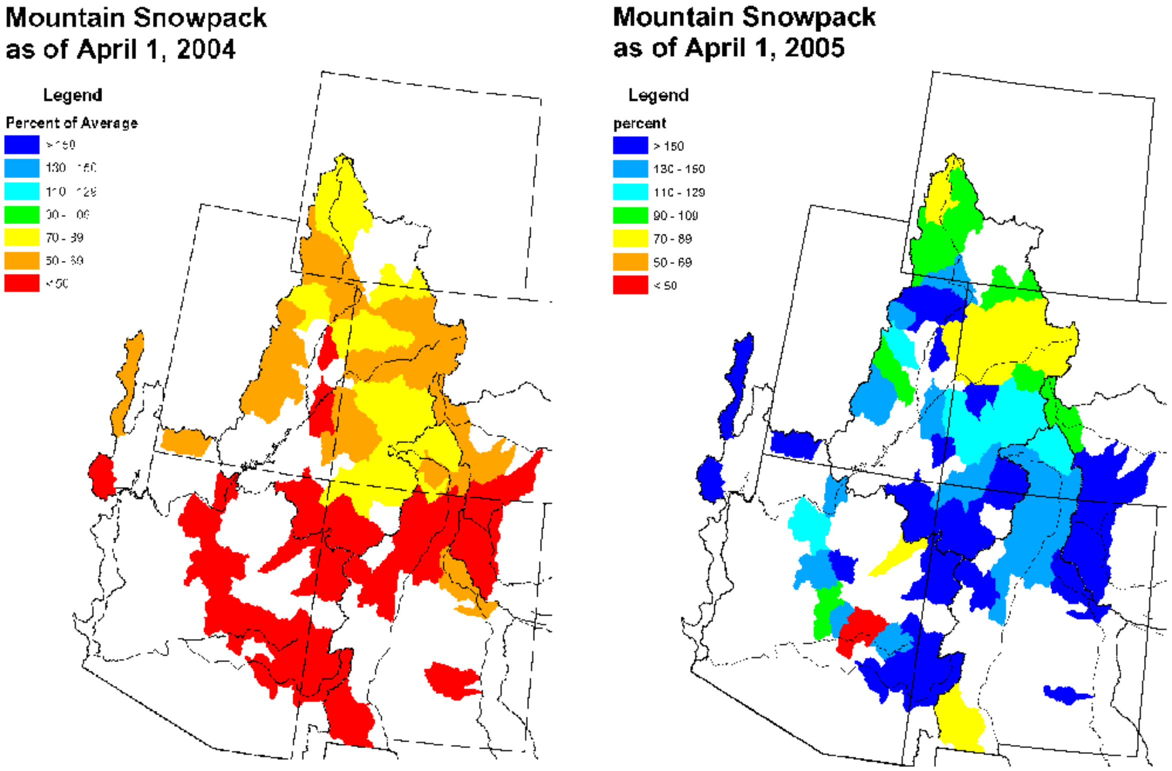

Figure 2. Snowpack expressed as percent of 30-year average in various sub-basins of the Colorado River basin, as of 1 April 2004 (left) and 1 April 2005 (right). Data are from SNOTEL sites operated by the National Resource Conservation Service (NRCS) and figures are from the NRCS National Water and Climate Center.

2.3. Use of SNOTEL Precipitation Data to Estimate Snowpack Ablation

To estimate snowpack ablation, we compared November 1 to April 1 accumulated gauge snowfall at 16 SNOTEL sites against April 1 SNODAS SWE there. November 1 is a nominal date after which most precipitation falls as snow rather than rain. The 16 sites were from Colorado, Utah, Wyoming, and Arizona, at dispersed geographic locations and elevations. Interestingly, the SNOTEL precipitation-to-SNODAS SWE ratios were 1.22 in 2004 and 0.89 in 2005, respectively. The latter ratio, indicative of greater snowpack water than precipitation, might reflect a problem with gauge precipitation measurement or the arbitrary November 1 start date of the snowfall season. There is significant gauge under catch of snowfall in wind-exposed locations that might explain much of the problem. The bottom line is that we cannot trust the SNOTEL gauge-measured seasonal precipitation to estimate seasonal melt of the snowpack. There is one other option to estimate melt. The SNODAS model outputs snow melt at the base of the pack. We post daily melt products on our Colorado web site (Hunter 2004). To generate seasonal melt, we would have to sum the daily values over an entire winter. This is beyond the scope of the current study but may be pursued later.

3. RESULTS AND INTERPRETATION

The reader is cautioned that water volumes resulting from increasing existing April 1 snowpacks via cloud seeding *do not necessarily equal runoff increases*. The latter increases may be changed by a given basin's hydrologic processes such as soil infiltration, antecedent soil moisture, slope and aspect, and vegetative cover. Other factors affecting a basin's precipitation-runoff relationship are spatial distribution of the snowpack, amount and timing of any rainfall on the pack, temperature, and evapotranspiration of snowmelt water.

There was a CREST-related analysis (Super and McPartland 1993) of snowpack-runoff relationships for fourteen watersheds in Colorado, Wyoming and Utah. The selected watersheds were not significantly affected by upstream trans-mountain or trans-basin diversions and not regulated by upstream reservoirs. This analysis performed a long-term linear regression of snow course/snow pillow SWE and stream gauge data and assumed 10% SWE increases from seeding. Correlation coefficients between the two datasets was low for some watersheds, usually because the snow courses/snow pillows were relatively low in elevation and didn't reflect higher altitude snowpack (this shortcoming could be alleviated by the spatially continuous SWE fields of SNODAS, if one were to do a new regression analysis with that system). Given the assumed 10% SWE increase, April to July seasonal runoff increases varied from 6% to 21%. This variation was attributed either to poor representation of the snow course/snow pillow SWE data or to differing basin hydrologic or meteorological characteristics, as related in the preceding paragraph. Porous geology such as sinkholes may divert meltwater away from stream gauges, leading to decreased runoff measurements, whereas impermeable soils such as clay may increase runoff percentages. Again, these complex factors will affect any additional runoff produced by seeding-induced precipitation increases and should be weighed when selecting target areas. It is logical to assume that the farther the target area is from the mainstem of the Colorado River, the greater the runoff losses at the river. Examples of such areas are the Wyoming potential targets at the northern extremity of the basin (see Fig. 1). On average, however, 10% runoff increases might be expected to result from 10% snowpack increases (Arlin Super, personal communication).

Table 4 lists the water volumes produced by 10% increases of the snowpack SWE on April 1 for existing target areas and for the potential target areas.

Table 4. Areas and water yields for 10% snowpack SWE increases from seeding, for existing (operational) seeding targets and potential new targets.

	Area (km^2)	April 1, 2004 (Dry) Yield (ac-ft)	April 1, 2005 (Wet) Yield (ac-ft)	Mean Yield 04-05 (ac-ft)
Existing Areas				
Utah	12,992	128,902	294,527	211,715
Colorado	17,767	240,852	499,190	370,021
Total	30,759	369,754	793,717	581,736
Potential Areas (All States) Total	13,611	217,890	352,978	285,434
Existing + Potential Areas Total	44,370	587,644	1,146,695	**867,170**

It seems unlikely that two years of SNODAS data would convey the long-term variance of precipitation across the Colorado River Basin, even if those two years exhibited a large variation about the mean in precipitation amounts. Nevertheless, **SNODAS** SWEs at the 16 Basin SNOTEL locations (see previous section) were compared to the 30-year (1971-2000) **SNOTEL** SWE averages. The 2004 SNODAS SWE mean for all sites was 12.5 inches and the 2005 mean was 20.5 inches. The 30-year average SNOTEL SWE for the sites is 17.9 inches, intermediate to the SNODAS SWE for the two years, and close to their mean of 16.5 inches. This calculation lends confidence that the target area-integrated means of the two-year SNODAS data represent a climatologically average year. These means are presented in the right-most column of Table 4.

It is instructive to compare these means with those of Table 1. The wet year (2005) is close to the Stanford Research and Twelve Basin liberal figures, whereas the mean is very close to the Twelve Basin conservative value. Using half of the Stanford figures again, that report states that “One year out of three, it [the yield] might be either lower than 550,000 or higher than 1,800,000 acre-feet.” The dry snow accumulation year ending April 1, 2004 is very close to the low figure of the Stanford study. The high figure of that study seems optimistic, especially since both Colorado and Utah suspend seeding operations when snowpack SWE exceeds certain percentages of normal. If one attempts to account for seasonal snowmelt (see previous section), the mean yield at lower right of Table 4 might be near 1 million acre-feet. This figure is close to that from the Stanford study and is intermediate to the conservative and liberal Twelve Basin values. This amount of water is significant for the Colorado River basin water balance; for example, it is two-thirds of the 1.5 million acre-feet of the river's annual flow that is legally obligated to Mexico.

These values should be considered approximate. Since they compare favorably to the estimates of two earlier studies, however, we have more confidence in them. There are many variables in determining the effectiveness of seeding, which could lead to substantial deviations from the assumed 10% augmentation used herein. Besides the choice of target areas, there are natural hydrologic and meteorological variables. Then there are those associated with seeding methods. For those methods to be effective, seeding materials must be dispersed in sufficient concentration in cloud regions with adequate supercooled liquid water and temperatures cold enough for the seeding materials to function as intended. An examination of these variables is beyond the scope of this study. There is an in-depth examination, however, in a recent Colorado seeding feasibility study (Super and Heimbach 2005).

4. CONCLUSIONS

Within the limitations of the SNODAS data set and stated uncertainties of our calculations we estimate that, for an **average** precipitation year in the Colorado River Basin, cloud seeding could generate an additional **one million acre feet** of water storage in the basin-wide snowpack. In drought years, seeding might produce about half that amount, or 500,000 acre feet. In wet years, more than one million acre feet could be produced, but how much more would be limited by seeding suspension criteria. These estimates are close to those of two older studies. Therefore, application of a modern, sophisticated snow modeling and assimilation system has produced similar water yields as the older studies and gives confidence that such yields are representative.

Acknowledgments. Many thanks to Ra Aman and Steffen Meyer for programming and GIS support. This project was sponsored by a grant from the Colorado Water Conservation Board (CWCB) entitled "A Winter Storm Climatology," and was administered by Reclamation Technical Service Center account number A1R175893350010000. We thank Joe Busto of the CWCB for his technical assistance and guidance. Don Griffith of North American Weather Consultants and Larry Hjermstad of Western Weather Consultants provided valuable insights, as did Drs. Arlin Super and Jim Heimbach. Thanks to Todd Adams of Utah Dept. of Water Resources and HDR Engineering of Denver for GIS data of existing seeding target areas.

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