APPLICATION OF A HYDROLOGIC MODEL TO ASSESS THE EFFECTS OF CLOUD SEEDING IN THE WALKER RIVER BASIN OF NEVADA

Douglas P. Boyle, Gregg W. Lamorey, and Arlen W. Huggins
Desert Research Institute
Reno, Nevada

Abstract. The focus of this study is to use a physically-based, distributed hydrologic model to estimate the impacts of cloud seeding efforts on the streamflow generated within the areas of the Walker River Basin targeted by the Nevada seeding program. The hydrologic model is calibrated using GIS information, model default values, and manual calibration to fit observed streamflow at a USGS surface water station within the Walker River Basin. The calibrated model is then used in two case studies that are designed to simulate a non-seeded condition and a seeded condition with a 10% increase in precipitation on the five target areas. The results from the two modeling case studies indicate that the additional precipitation applied in the seeded case results in increases in evaporation and runoff from the target areas but does not significantly impact the storages of moisture in the groundwater and soil zone for all of the five target areas. The fraction of seeding-increased precipitation that resulted in streamflow varied from 49% to 89% among the different target areas. The remainder of the additional precipitation resulted in evapotranspiration from the target areas.

1. INTRODUCTION AND SCOPE

There are more than a dozen wintertime cloud seeding programs in the western U.S. whose primary goal is to increase snowfall over specific drainage basins in order to subsequently increase stream runoff in the spring and summer months. An accurate assessment of the impacts of any cloud seeding operation on streamflow runoff requires detailed knowledge of the spatial and temporal increases in precipitation due to the cloud seeding activities and the watershed response to the additional precipitation. Obtaining this knowledge is often difficult or impossible due to the budget and time constraints associated with the field effort required to collect the necessary data. For projects in the western U.S. the documentation of seeding effects has been accomplished by assessments of randomized experiments such as in Mooney and Lund (1969), and by highly focused nonrandomized experiments. Latter experiments studied in-cloud microphysical changes, snowfall characteristics and precipitation rate changes at the surface, and evidence of the seeding material in snow layers in seeding target areas (e.g., Super, 1999, Deshler et al., 1990 and Warburton et al., 1996). Some operational projects have compared stream runoff from seeded and unseeded basins as part of their evaluation (Henderson, 1966). Also, McGurty (1999) used snow chemistry and a relationship between snow density and silver concentration to estimate increases in snowfall and runoff in a Sierra Nevada target area. While the prediction of additional runoff due to seeding efforts has not been routinely attempted, there have been preliminary studies conducted in the Upper Colorado River Basin (Super and McPartland, 1993).

Within Nevada's Weather Damage Modification Program (WDMP), a cooperative research effort with the U.S. Bureau of Reclamation (Hunter et al., 2005), hydrologic modeling has been incorporated into the research to predict how changes in the snowpack from cloud seeding will alter runoff in the affected streams of targeted basins. This research involves the application of a hydrologic model to simulate watershed response to additional precipitation from cloud seeding activities through the different hydrologic processes (snowpack evolution, evaporation and transpiration, infiltration, soil moisture movement, runoff, and streamflow). This research component was "piggy-backed" onto cloud seeding operations that are routinely conducted in the Walker Basin by the State of Nevada.

This paper presents results from the hydrologic modeling of the Walker River Basin whose headwater region is on the eastern (mainly downwind) side of the Sierra Nevada just north of Yosemite National Park. During the winter of 2003-04 this headwater region was targeted by several ground seeding generators and occasionally by aircraft seeding. The hydrologic model is initially calibrated during a period when there were no known cloud seeding operations. Next, the hydrologic model is used to investigate the impacts of cloud seeding in the Walker River Basin through two case studies. In the first case study, the model is run forward in time through the 2003-04 winter, assuming the target areas are not impacted by ground or aircraft cloud seeding activities. In the second case, cloud seeding activities are assumed to increase the total precipitation on the target areas during the 2003-04 winter by 10%. Although storms over the Walker Basin were routinely seeded in 2003-04 and snow profiles verified the presence of seeding material in a high percentage of snow layers in several specific sub-basin regions (Huggins et al., 2005), the actual percentage increase in snowfall was not verified physically. The components of the water balance (evapotranspiration, groundwater, soil moisture, and runoff) are estimated and compared for both cases.

The paper is organized as follows: Section 2 contains a description of the Walker River Basin study area, the available data, and a discussion of the Nevada cloud seeding operations. The hydrologic modeling approach is described in section 3. Results of the model case studies are presented in section 4, and the results and future extensions of the research are discussed in section 5.

2. STUDY AREA

2.1 Description of Walker River Basin

The Walker River Basin area is approximately 7,029 km^2, and ranges in elevation from 1,300m near Walker Lake to over 3,500m in the headwater areas of the Sierra Nevada (Figure 1). The Walker River generally flows from south to north until reaching the confluence of the West and East Walker Rivers, where it then flows southeast to the terminal Walker Lake. This study is focused on the upper portion of the Walker River (above the confluence of the West and East Walker Rivers), where the majority of its streamflow is generated through snow accumulation and melt processes (Figure 1).

2.2 Streamflow and Meteorological Data

The United States National Resources Conservation Service (NRCS) maintains five SNOpack TELemetry (SNOTEL) sites within Walker River Basin that provide real-time daily estimates of snow water equivalent (SWE), snow depth, precipitation, and temperature at each site (Figure 1). All of these sites are at generally high elevations (2,195 to 2,866m), with historic SWE, snow depth, and precipitation data available from the early to mid 1980s to the present. Temperature data for each site are generally available from the mid to late 1980s to the present.

The United States National Weather Service (NWS) maintains four weather stations within the Walker River Basin that provide real-time daily estimates of precipitation and temperature (Figure 1). All of these sites are generally lower in elevation (1,311 to 1,972m), with historic precipitation and temperature data available from before the1980s to the present.

The United States Geological Survey (USGS) maintains ten surface water stations that provide continuous daily streamflow estimates at various locations within the upper Walker River Basin (Figure 1). Some of these stations have historic daily records available from before the 1980s through the present, while others date back to the early 1990s. Many of these stations, however, have significant ungauged diversions, returns, or reservoir operations within the area, altering measured streamflow at the station. In some cases the stations had significant periods of missing values and therefore were not useful for this study.

Basin	Area (km^2)	Mean Elevation (m)	Vegetation Type	Soil Type
Sierra Crest	619	2808	95% trees 5% grasses	100% sand
Sweetwater Mountains	259	2735	96% trees 4% grasses	100% sand
Bodie Hills	202	2454	100% trees	61% sand 39% loam
Pine Grove Hills	249	2223	100% trees	93% sand 7% loam
Wassuk Mountains	195	2124	100% trees	100% sand

Table 1. *Hydrologic characteristics of the five areas targeted by cloud seeding.*

2.3 Nevada State Cloud Seeding Program Operations in the Walker River Basin

There are five high altitude areas within the Walker River Basin that are targeted by the Nevada State Cloud Seeding Program's operations: Sierra Crest, Bodie Hills, Wassuk Mountains, Sweetwater Mountains, and Pine Grove Region (Figure 1). These are mountainous, snow-dominated areas that range in size from almost 200 km^2 to over 619 km^2, and in elevation from 2,124m to 2,808m (Table 1). The vegetation is predominantly coniferous forest in the Sierra Crest, with a mix of pinion pine forest, desert shrub and grasses in the other areas (Table 1). The soils range from mostly sand for the Sierra Crest, Wassuk Mountains, and Sweetwater Mountains, to a mix of sand and loam for the Bodie Hills (61% sand and 39% loam) and the Pine Grove Region (7% sand and 93% loam).

Cloud seeding in the Walker Basin dates back to the 1980s. The current Nevada program that includes eight ground-based seeding generators and about 10 aircraft seeding flights per season, however, has existed for only the past three seasons. The locations of the eight ground generators and the most commonly used seeding flight tracks are shown in Figure 1. Both ground generators and aircraft solution-burning generators currently use a mixture that produces silver chloroiodide – salt ice nuclei similar to those described by Feng and Finnegan (1989). In water-saturated conditions at temperatures below -5^{o}C, these particles are fast acting condensation freezing nuclei. Ground generators release about 25 g h^{-1} of seeding material, and each aircraft burner releases about 150 g h^{-1}. The aircraft on occasion also use burn-in-place flares manufactured by Ice Crystal Engineering, which also produce fast-acting condensation freezing nuclei.

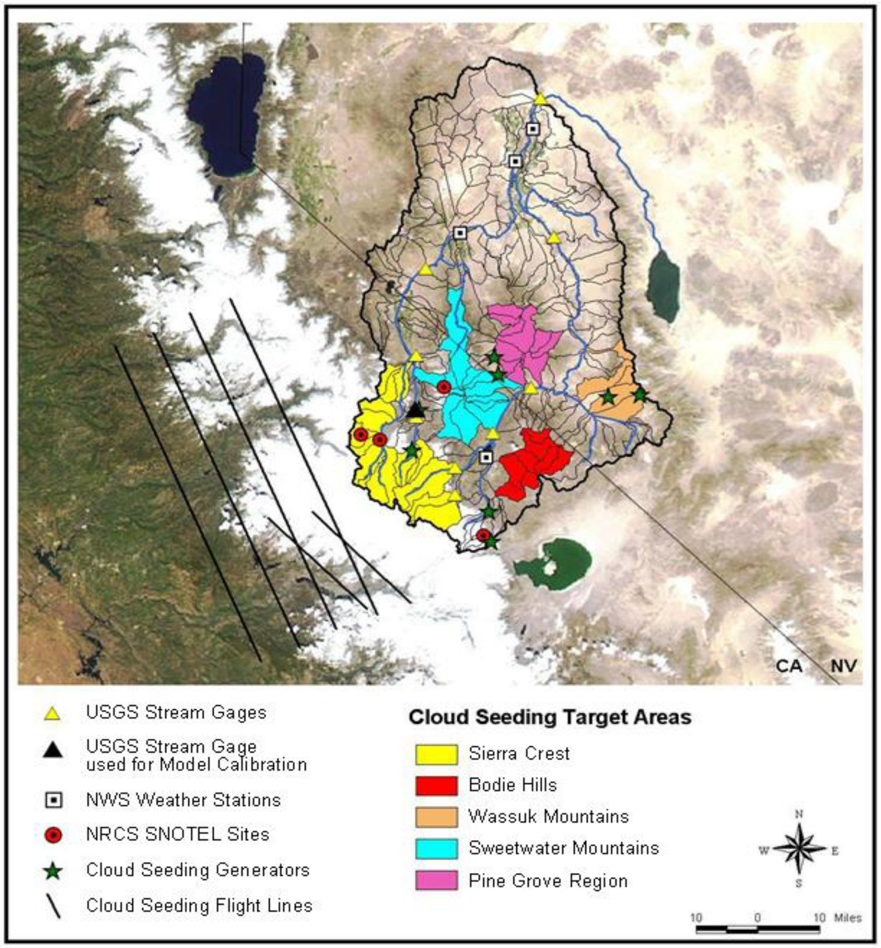

***Figure 1.** Location of Walker River Basin study area and five target areas affected by the Nevada cloud seeding activities.*

During the 2003-04 season the Nevada Program conducted 26 ground seeding operations in the Walker Basin, with a total of about 1015 hours of generator operation and the release of 27,400 g of seeding material. There were 12 aircraft flights targeting the Walker Basin, during which an additional 3,350 g of seeding material was released. The collection and trace chemical evaluation of snow samples at four sites in the Walker Basin were undertaken within a separate WDMP research task. The high percentage of silver found in the snow profiles at the Sierra Crest, Sweetwater Mountains and Bodie Hills sites indicated that they were routinely targeted by seeding operations (Huggins et al., 2005). Samples were not obtained from the Wassuk Mountains or Pine Grove region due to access limitations. Although lacking a target-control evaluation to quantify seeding results, the trace chemical assessment supports the distribution of estimated seeding results that are used in simulations involving the hydrologic model, which is the subject of the following section.

3. HYDROLOGIC MODELING OF WALKER RIVER BASIN

3.1 Overview of Modeling Approach

This section presents a description of the hydrologic modeling approach applied to the upper Walker River Basin, to estimate the impacts of cloud seeding on the streamflow within the areas targeted by the Nevada seeding program in water year 2004. In the following subsections, a brief description of the hydrologic model, the calibration process, and seeded and unseeded cases are provided. Results from the calibration process and the two cases are provided in Section 4.

3.2 Precipitation Runoff Modeling System

The USGS Precipitation-Runoff Modeling System (PRMS) (Leavesley et al., 1983, Leavesley and Stannard, 1995, and Leavesley et al., 2006) is a modular design, distributed-parameter, physical-process watershed model. The PRMS model was developed to evaluate the effects of various combinations of precipitation, temperature, and land use on watershed response, e.g., snowpack, soil moisture, groundwater, evapotranspiration, and streamflow. The PRMS software is available within the USGS Modular Modeling System (MMS) (Leavesley et al., 1996 and Leavesley et al., 2006) as a set of process algorithms that together simulate the dominant processes of the watershed response. While MMS supports the development, integration, and application of new process modules, the standard MMS-PRMS modules were selected for use in this study.

The MMS-PRMS allows the user to partition the watershed into hydrologic response units (HRU) based on different characteristics of a watershed, e.g., slope, aspect, stream network, elevation etc. The delineation, characterization, and parameterization of the watershed can be carried out with geographic information system (GIS) technology within the ArcInfo (ESRI, 1992) computer software and USGS Weasel interface (Leavesley et al., 2002 and Leavesley, et al., 2006). The GIS Weasel is used to delineate, characterize, and parameterize topological, hydrological, and biological basin features, for use in the MMS-PRMS modeling approach. The GIS Weasel utilizes relationships developed for commonly available spatial estimates of soil, vegetation, and topographical properties, to estimate values for various MMS-PRMS model parameters, for each HRU. For MMS-PRMS parameters that are not estimated using the GIS Weasel, default parameter values and ranges are provided in the MMS-PRMS software.

To simulate the watershed response in a daily mode, the MMS-PRMS requires daily estimates of precipitation, minimum daily temperature, and maximum daily temperature at the centroid of each HRU. Since measurements of these driving variables are almost never available at the centroid of each HRU, several methods have been developed to relate measured values at known locations (e.g., NRCS SNOTEL and NWS stations) to each HRU centroid (Hay et al., 2002). One approach utilizes the spatial (4km x 4km) relationships of average monthly precipitation and temperature from the Spatial Climate Analysis Service at Oregon State University (Daly et al., 2001) using a Parameter elevation Regressions on Independent Slopes Model (PRISM). In this approach, the daily value for each driving variable (e.g., precipitation) at the centroid of each HRU is estimated by multiplying the observed daily precipitation value (from NRCS SNOTEL and/or NWS stations) by the ratio of the average monthly PRISM precipitation value at the HRU centroid to the average monthly precipitation value at the observation site. Then a time series for each driving variable can be developed at each HRU centroid. If there is more than one observation site available, the same process can be used to estimate a time series at the HRU centroid from each observation site. During the model run, the average value from the available time series is used for each time step. This approach works well when there are periods of missing data at one or more of the observation sites.

3.3 Application and Calibration of MMS-PRMS Model

In this study, the MMS-PRMS model was applied to the entire upper Walker River Basin. The delineation of the upper Walker River Basin and partitioning of the HRUs were carried out with ArcInfo computer software and the USGS Weasel interface, based on the location of USGS surface water station locations and hydrologic characteristics of the watershed (e.g., slope, aspect, stream network, elevation, etc.). The modeling extent, HRU delineation, and target areas are shown in Figure 1.

Average monthly precipitation and temperature estimates from PRISM were used to develop spatial-temporal relationships between precipitation and temperature observations at the four SNOTEL and four NWS stations and the centroids of each HRU. With these relationships, the time series of daily values of precipitation, minimum temperature, and maximum temperature from each of the SNOTEL and NWS sites was available for use on each HRU for the period 1 October 1980 through 30 September 2004. These relationships were used to estimate the daily value of each driving variable (precipitation, minimum temperature, and maximum temperature) at an HRU from all of the four SNOTEL and four NWS sites.

The GIS Weasel was used to estimate initial values for all HRU parameters related to soils, vegetation, and topography, based on the digital elevation model, spatial soils information, and spatial vegetation information. All remaining MMS-PRMS model parameters were initially assigned default values from the MMS-PRMS documentation and software.

The MMS-PRMS model was initially run using the combination of GIS Weasel and default parameters to simulate observed streamflow at the West Walker below the Little Walker surface water station, for the period 1 October 1980 through 30 September 1992. This surface water station was selected because of its extensive historic record and because there are no significant diversions, returns, or reservoir operations within the area contributing to the station. The period was selected because there were very minimal cloud seeding operations in the Walker River Basin prior to the 1992-93 winter. Based on the initial results from this model run, the following four additional parameters were manually adjusted (same value of each parameter for each HRU) to improve the simulation of streamflow at the West Walker below Little Walker surface water station: (1) *snowinfl_max* - maximum infiltration rate for snowmelt, in cm/day (snowinfl_max set to 10 cm/day); (2) *soil2gw_max* - the amount of the soil water excess for an HRU that is routed directly to the associated groundwater reservoir each day (soil2gw_max set to 0.5 cm); (3) *tmax_allsnow* - if HRU maximum temperature is less than or equal to this value, precipitation is assumed to be snow (tmax_allsnow set to 1.1 ^{o}C); (4) *tmax_allrain* - if HRU maximum temperature is greater than or equal to this value, precipitation is assumed to be rain (tmax_allrain set to 7.2 ^{o}C).

The results of the calibrated model are described in section 4, below. Unfortunately, the remainder of the surface water stations within the upper Walker River Basin could not be used for calibration, since each had at least one of the following: insufficient historic record, significant number of missing values, significant ungauged diversions, returns, or reservoirs. As a result, the parameter values for the remaining HRUs (those not directly contributing to the West Walker below Little Walker surface water station) were set at a combination determined by the GIS Weasel, MMS-PRMS default values, and values determined through manual calibration on the West Walker below Little Walker.

3.4 MMS-PRMS Non-Seeded and Seeded Modeling Cases

Since the state of Nevada has been performing different types cloud seeding operations in the Walker River Basin from 1992 to present, the development of a non-seeded case over that entire period would be difficult. Rather than try to understand their impact over the entire period, this study is focused on understanding how the Nevada cloud seeding operations over the 2003-04 winter may have impacted streamflow from only the target areas. To accomplish this, two cases or scenarios (non-seeded and seeded) were designed for the target areas that, when compared with each other, provide an estimate of how additional precipitation from cloud seeding moves through the hydrologic cycle in the target areas (based on the MMS-PRMS model). Several assumptions were made in the development of each case, as described in the next two paragraphs.

For the non-seeded case, it was assumed that three of the four SNOTEL sites which are located within a target area were impacted by the cloud seeding operations. It was also assumed that in target areas only, cloud seeding operations resulted in a 10% increase in precipitation over what would have occurred without cloud seeding. As a result, the observed time series of precipitation for each of the three SNOTEL sites within the target areas was reduced by 11% (non-seeded precipitation = seeded precipitation/110%) during the months of November through March, when cloud seeding operations were underway. These modified time series were used with the remaining SNOTEL and four NWS sites (which were assumed to not be impacted by cloud seeding since they are outside the target areas) to drive the MMS-PRMS model forward from 1 October 1992 through 30 September 2004, to simulate the non-seeded case.

The seeded case utilized the same modified precipitation time series that was used for the non-seeded case, except that the precipitation from November through March was increased by 10% for the HRUs located in the target areas. While there are other ways to develop these cases, given the constraints of the approach used to spatially distribute precipitation from the observation sites to the HRU centroids, this approach provides a reasonable way to estimate how additional precipitation from cloud seeding moves through the hydrologic cycle in the target areas.

4. RESULTS

4.1 Calibration of MMS-PRMS Model

The streamflow simulated with MMS-PRMS for the West Walker below Little Walker is plotted in Figure 2 with observed values for the calibration period, 1 October 1980 through 30 September 1992. The plot reveals that the MMS-PRMS model does a reasonable overall job of simulating the observed daily flows. While the model generally matches the systematic rise and fall of the observed hydrograph, it tends to over predict a few of the early peaks and under predict a few of the mid to late peaks. These behaviours are most likely related to poor or missing temperature data. For example, several of the high altitude SNOTEL sites used in this study did not begin recording daily temperature until the mid to late 1980s. Furthermore, the lower elevation NWS sites tend to be in areas susceptible to temperature inversions in the late winter and spring, when snow melt may be occurring higher in the watershed. In the MMS-PRMS model, daily input temperature determines the form of the precipitation (snow or rain) so subtle errors in temperature data on days with large precipitation amounts when the temperature is near freezing can cause disproportional errors in runoff and water balance resulting in lower efficiency measures. These suspected low temperature errors were the primary reason for selecting the four MMS-PRMS parameters (snowinfl_max, tmax_allsnow, and tmax_allrain) for adjustment in the calibration process.

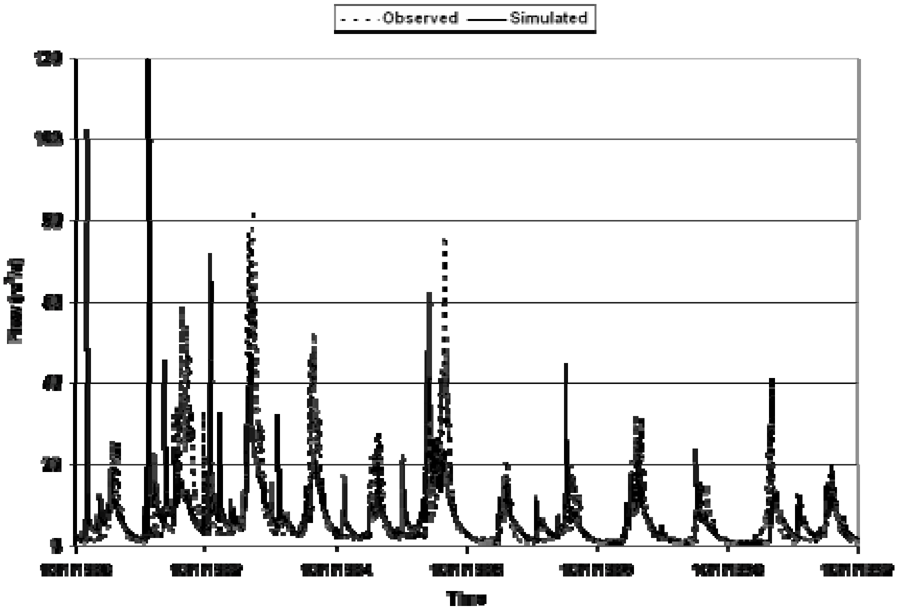

Figure 2. Streamflow hydrograph for the calibration period on the Walker River below the Little Walker. The streamflow simulated with MMS-PRMS is shown as a black line and the observed streamflow is shown as black dots.

Basin	ΔPrecip. from seeding (cm)	ΔET (cm & % diff)	ΔRunoff (cm & % diff)	ΔGround Water Storage (cm & % diff)	ΔSoil Storage (cm & % diff)
Sierra Crest	6.61	2.64 (40%)	4.12 (62%)	-0.17 (-2%)	0.02 (0%)
Sweetwater Mountains	4.30	2.25 (52%)	2.11 (49%)	-0.05 (-1%)	-0.01 (0%)
Bodie Hills	2.75	0.95 (34%)	1.81 (66%)	0.00 (0%)	-0.01 (0%)
Pine Grove Hills	3.13	1.08 (35%)	2.04 (65%)	0.01 (0%)	0.00 (0%)
Wassuk Mountains	2.51	0.26 (10%)	2.23 (89%)	0.02 (1%)	0.00 (0%)

Table 2. *Changes in simulated components of annual water balance in cm/year (volume divided by target area) due to 10% increase in precipitation in the five target areas.*

Three efficiency measures were used to evaluate the performance of the MMS-PRMS in terms of overall fit to the observed streamflow; the Nash Sutcliff (NS) efficiency measure, the root mean square error (RMSE), and the percent overall bias (PBIAS). The NS value of 0.49 and the RMSE value of 7.4 $m^3 s^{-1}$ indicate that while the model did a reasonably good job of fitting the general behaviour of the overall hydrograph, there were some problems in the fitting some of the higher flows. The PBIAS value of -6.8% indicates that while the MMS-PRMS model did a good job of simulating the overall volume of streamflow during the calibration period, there was a slight overall underestimation of the total volume. The quality of the calibration of the MMS-PRMS model for this basin is fairly typical for watershed models of the northern Sierra Nevada (Jeton, 1999 and 2000).

4.2 <u>MMS-PRMS Non-Seeded and Seeded Modeling Cases</u>

The results from the MMS-PRMS model runs for both the non-seeded and seeded cases are shown for all five target areas in Table 2. Column 2 of the table presents the additional 10% precipitation applied to each target area over winter 2003-04 for the seeded case. Columns 3-6 present the additional amount of evapotranspiration, runoff, change in ground water storage, and change in soil moisture (in cm and %) resulting from the additional 10% precipitation, applied to each target area during the period 1 October 2003 through 30 September 2004. For example, in the Sierra Crest target area, 40% (or 2.64 cm) of the additional precipitation (6.61 cm) resulted in evapotranspiration and 62% (or 4.12 cm) resulted in runoff, 2% (or 0.17 cm) remained in the groundwater storage, and approximately 0% (or 0.02 cm) remained in the soil moisture zone. Notice that the additional 10% of precipitation in the seeding case resulted in additional evapotranspiration and runoff but did not significantly increase (or decrease) the amount of water stored in the groundwater or soil moisture zones for any of the five target areas.

While the Sierra Crest target area had the largest amount of additional runoff (4.12 cm), the Wassuk Mountains target area had the greatest fraction of runoff (89%) from the additional precipitation (2.23 cm). Also, while the Bodie Hills target area had the least amount of runoff (1.81 cm) from the additional precipitation (3.13 cm), the Sweetwater Mountains target area had the lowest fraction of runoff (49%) from the additional precipitation (4.30 cm). These results are primarily attributable to the differences in evapotranspiration from the additional precipitation between the areas (52% or 2.25 cm for the Sweetwater Mountain target area and 10% or 0.26 cm for the Wassuk Mountains target area).

Figure 3a-b present the temporal distribution of the volumetric differences in evapotranspiration, runoff, and SWE for the seeded and non-seeded cases in the Wassuk Mountains and Sweetwater Mountains target areas. In these plots, the daily values of ET, runoff, and SWE simulated in the non-seeded case were subtracted from the daily values of ET, runoff, and SWE simulated in the seeded case for both the Wassuk Mountains (Figure 3a) and the Sweetwater Mountains (Figure 3b) target areas. Notice that the majority of the increase in runoff for both target areas occurs after the peak in the increase in SWE and remains high until the increased SWE is depleted. The primary differences between the two target areas are that the increased SWE values are much larger and last much longer into the season for the Sweetwater Mountains target area than those in the Wassuk Mountains target area. Evapotranspiration begins for both target areas at nearly the same time; however, the values for the Sweetwater Mountains target area are much larger and last much longer into the season that those in the Wassuk Mountains target area.

The MMS-PRMS simulation time series of snow water equivalent, soil moisture, and evapotranspiration for the Sweetwater Mountains (dashed line) and Wassuk Mountains (solid line) target areas are plotted in Figures 4a-c. Figure 4a shows the timing of the evapotranspiration for the Sweetwater Mountains and Wassuk Mountains target areas. The vertical dash-dot line on the plot represents the approximate date (10 April 2004) when the potential evapotranspiration demand can be satisfied by the moisture in the soil zone through transpiration from the vegetation. The significant difference in snow water equivalent simulated by MMS-PRMS for the Sweetwater Mountains and Wassuk Mountains target areas is clearly shown in Figure 4b.

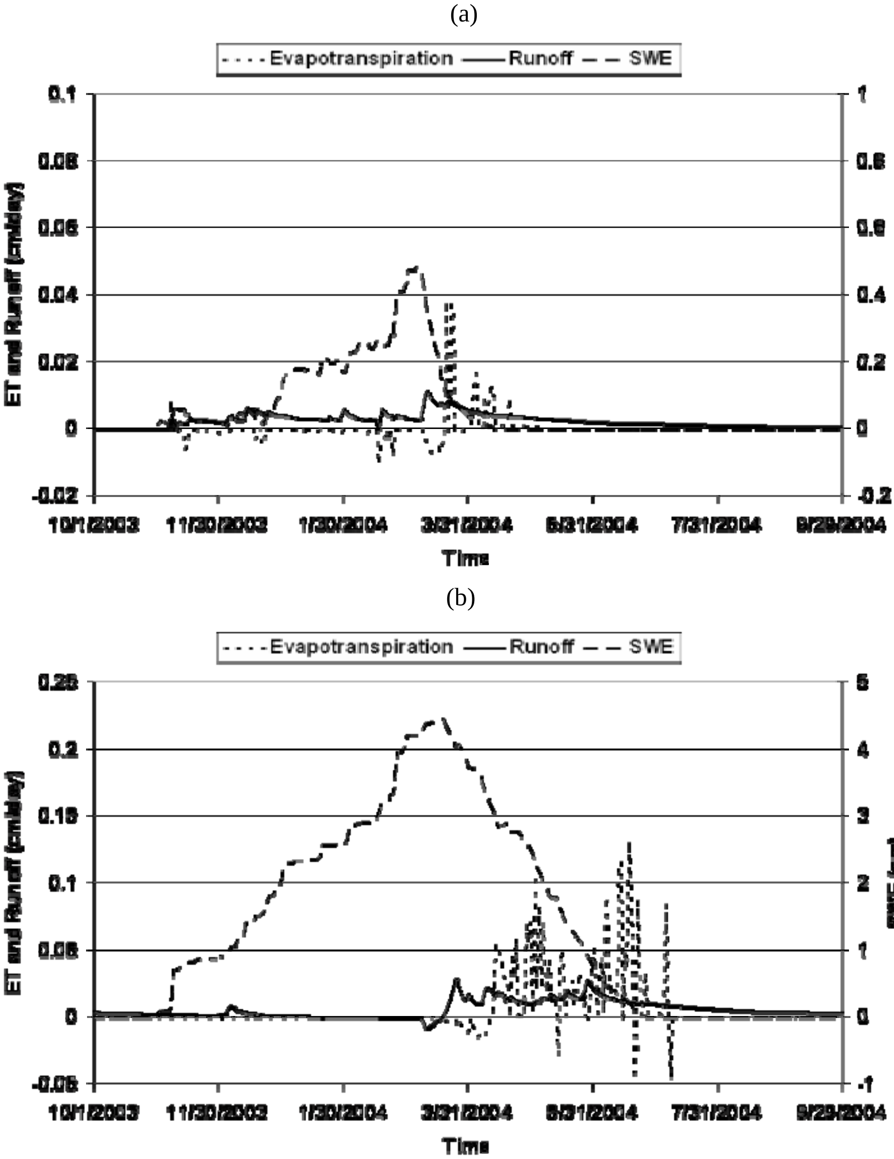

Figure 3. *Temporal distribution of the simulated volumetric differences in evapotranspiration (dots), runoff (solid line), and SWE (dashed line) for the seeded and non-seeded cases in the Wassuk Mountains (a) and Sweetwater Mountains (b) target areas.*

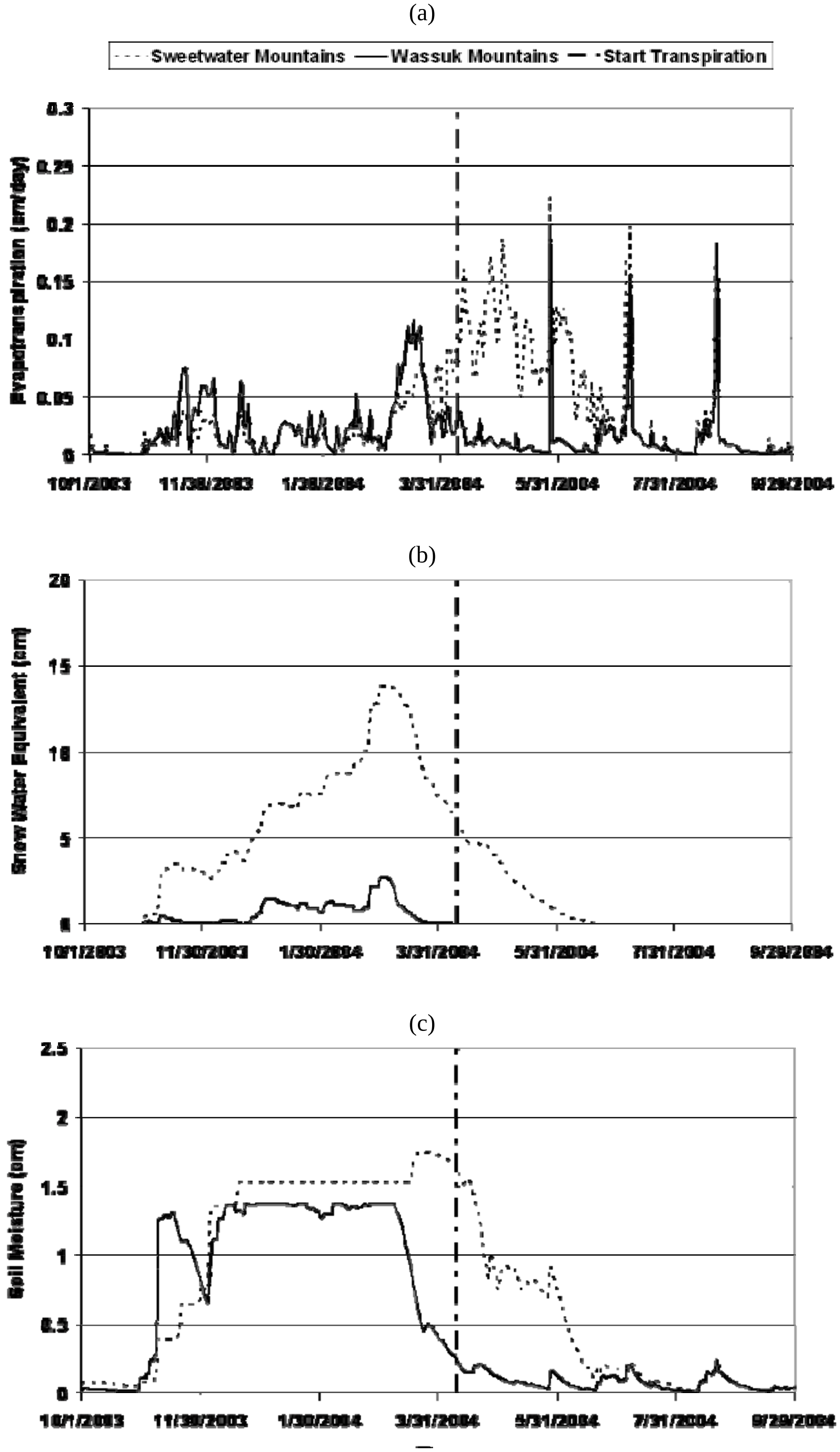

Figure 4. *Temporal distribution of the simulated evapotranspiration volume (a), snow water equivalent volume (b), and soil moisture volume (c), for the Sweetwater Mountains (dots) and Wassuk Mountains (solid line) target areas. The vertical dash-dot line represents the approximate date when the potential evapotranspiration demand can be satisfied by the moisture in the soil zone through transpiration from the vegetation.*

This difference is most likely related to the differences in elevation and meteorology of the two target areas. The Sweetwater Mountains target area is higher than the Wassuk Mountains target area (2,735m vs. 2,124m) and receives more precipitation in the form of snow than the Wassuk Mountains. The Sweetwater Mountains target area is also impacted less by rain shadow effects from the Sierra Crest than the Wassuk Mountains target area and thus receives more precipitation. Notice that the snow pack has completely melted in the Wassuk Mountains target area prior to 10 April 2004, while significant snowpack remains in the Sweetwater Mountains target area. As a result, the potential evapotranspiration demand in the Wassuk hills after 10 April 2004 can only be satisfied by the amount of moisture already in the soil zone (see Figure 4c), while the Sweetwater Mountains target area has sufficient snowpack remaining to recharge the moisture in the soil zone well after 10 April 2004.

5. SUMMARY AND CONCLUSIONS

In this paper, the MMS-PRMS model was applied to five target areas in the Walker River Basin to investigate the watershed response to the Nevada cloud seeding operations. Parameter values for the MMS-PRMS model were estimated using GIS information, model default values, and manual calibration to fit observed streamflow at a USGS surface water station within the Walker River Basin. The calibrated model was then used in two case studies that were designed to simulate a non-seeded condition and a seeded condition with a 10% increase in precipitation on the five target areas. A comparison of the hydrologic components (evapotranspiration, runoff, groundwater, and soil moisture) from the hydrologic model simulations was then made to understand how the precipitation from the cloud seeding efforts might impact the watershed response.

The two modelling case studies indicated that the additional precipitation applied in the seeded case resulted in increases in evaporation and runoff from the target areas, but did not significantly impact the storages of moisture in the groundwater and soil zone for all of the five target areas. The fraction of the additional precipitation that resulted in streamflow varied from 49% to 89% among the different target areas. The remainder of the additional precipitation was found to leave the target areas as evapotranspiration. A detailed analysis of the MMS-PRMS estimates of evapotranspiration, SWE, and soil moisture fluxes indicated that the timing of the transpiration from the vegetation, in combination with the timing of the snowpack melting, were directly related to the amount of soil moisture available to satisfy the potential evapotranspiration demand in each target area. In general, the target areas with larger overall snowpack had a larger fraction of the additional precipitation result in evapotranspiration, because there was more melt water available to recharge the soil moisture and satisfy the potential evapotranspiration demand. This point was highlighted in the Wassuk Mountains target area where the lowest amount of additional precipitation was derived from seeding, yet the area produced the second highest amount of additional streamflow. The lower mean elevation of the Wassuk Mountains may have been an important factor in the early runoff for the target area – the snowpack was able to melt earlier in the season before significant transpiration processes began. The vegetation and soils were similar in all five target areas and did not appear to be significant factors in differences among the target areas.

The results and conclusions presented in this study are limited to the uncertainties related to the application of the MMS-PRMS model to each target area under the seeded and non-seeded conditions. The calibration process indicated, however, that the model reasonably simulated the overall watershed streamflow response at the USGS surface water station at Walker River below Little Walker. There are no known additional hydrologic data to evaluate the model’s ability to accurately partition the precipitation into the different hydrologic components on the target areas. As a result, the authors of this paper do not claim that the results presented in this study accurately reflect the increase in streamflow to the Walker River Basin from the Nevada State Cloud Seeding Program cloud seeding operations in the winter 2003-04. There are still too many unknowns concerning the ability of the cloud seeding operations to achieve the assumed 10% seasonal increase in precipitation. Rather, we intend for the results to provide the operators of the Nevada State Cloud Seeding Program and water managers in the Walker River Basin with a better understanding of how the different targeted regions of the watershed respond to additional precipitation (volume and timing of additional runoff), which in turn may promote more efficient cloud seeding and water management activities.

Research aimed at further understanding the relationship between the Nevada State Cloud Seeding Program’s cloud seeding activities and impacts to the watershed response is ongoing. Future work will include the use of trace chemistry results from WDMP snow sampling efforts to better define the targeted areas affected by cloud seeding, plus additional hydrologic modeling sensitivity tests. The results of this work will be reported as soon as practicable and we invite dialog with others interested in these topics.

Acknowledgements. Partial financial support for this research was provided by the state of Nevada through funding to DRI for the Nevada State Cloud Seeding Program, and by the U.S. Department of Interior Weather Damage Modification Program in Nevada through Cooperative Agreements 03-FC-81-0924 and 03-FC-81-0890 between DRI and the U.S. Bureau of Reclamation.

6. REFERENCES

Daly, C., G.H. Taylor, W. P. Gibson, T.W. Parzybok, G. L. Johnson, P. Pasteris. High-quality spatial climate data sets for the United States and beyond. *Transactions of the American Society of Agricultural Engineers*, **43**, 1957-1962, 2001.

Deshler, T., D.W. Reynolds and A.W. Huggins, 1990: Physical response of winter orographic clouds over the Sierra Nevada to airborne seeding using dry ice or silver iodide. *J. Appl. Meteor.*, **29,** 288-330.

ESRI (Environmental Systems Research Institute), ARC/INFO 6.1 User's Guide. Redlands, CA, 1992.

Feng, D. and W.G. Finnegan, 1989: An efficient, fast functioning nucleating agent – AgI•AgCl-4NaCl. *J. Wea. Mod.*, **21,** 41-45.

Hay, L.E., Clarke, M.P., Wilby, W.J., Gutowski, W.J., Leavesley, G.H., Pan, Z., Arritt, R.W., and Takle, W.S., Use of regional climate model output for hydrologic simulations, *J. Hydrometeorology*, **3,** 571, 2002.

Hunter, S.M., J. Medina, and D. A. Matthews. The Weather Damage Modification Program, 2005: *16th Conference on Planned and Inadvertent Weather Modification*, Paper 7.1. American Meteorological Society, San Diego, CA, 9-13 January 2005.

Huggins, A.W., P.R. Edwards and J.R. McConnell, 2005: Summary of trace chemical and physical measurements of snowfall in two Nevada cloud seeding target areas. Preprints *16th Conference on Planned and Inadvertent Weather Modification*, Amer. Meteor. Soc., San Diego, CA, 9-13 January 2005.

Jeton, A.E., Precipitation-Runoff Simulations for the Lake Tahoe Basin, California and Nevada: U.S. Geological Survey Water-Resources Investigations Report 99-4110, 61 p., 1999.

Jeton, A.E., Precipitation-runoff simulations for the upper part of the Truckee River Basin, California and Nevada: U.S. Geological Survey Water-Resources Investigations Report 99-4282, 41 p., 2000.

Leavesley, G.H., R.W. Lichty, B.M. Troutman, and L.G. Saindon, Precipitation-runoff modeling system–User's Manual, U.S.G.S., Water Resources Investigation Report 83-4238, 1983.

Leavesley, G.H. and L.G. Stannard, The precipitation-runoff model system–PRMS, in *Computer Models of Watershed Hydrology*, Singh, V.P. Ed. Water Resources Publications, Highlands Ranch, CO, 281, 1995.

Leavesley, G.H., P.J. Restrepo, S.L. Markstrom, M. Dixon, and L.G. Stannard, The modular modeling system - MMS: User's Manual, USGS Open File Report 96-151, 142 p, 1996.

Leavesley, S.L. Markstrom, P.J. Restrepo, and R.J. Viger, A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrologic modelling. *Hydrologic Process*, **16,** 173, 2002.

Leavesley, G.H., S.L. Markstrom, and R.J. Viger, USGS modular modeling system (MMS)–precipitation-runoff modeling system (PRMS), in *Watershed Models*, Singh, V.P. and Frevert, D.K., Eds. CRC Press, Boca Raton, FL, 653, 2006.

McGurty, B.M., 1999: Turning silver into gold: Measuring the benefits of cloud seeding. *Hydro. Review*, **18,** 2-6.

Mooney, M. L. and G. W. Lunn, 1969: The area of maximum effect resulting from the Lake Almanor randomized cloud seeding experiment. *J. Appl. Meteor.*, **8,** 68-74.

Super, A.B., 1999: Summary of the NOAA/Utah Atmospheric Modification Program: 1990-1998. *J. Weather Mod.*, **31,** 51-75.

Super, A.B. and J.T. McPartland, 1993: Preliminary estimates of increased runoff from additional high elevation snowfall in the Upper Colorado River Basin. *Journal of Weather Modification*, **25**, 74-81.

Warburton, J.A., S.K. Chai, R.H. Stone and L.G. Young, 1996: The assessment of snowpack enhancement by silver iodide cloud-seeding using the physics and chemistry of the snowfall. *J. Weather Mod.*, **28,** 19-28.