

# OPTIMIZING CLOUD SEEDING FOR WATER AND ENERGY IN CALIFORNIA

*Prepared For:*  
**California Energy Commission**  
Public Interest Energy Research Program

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## Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

*Optimizing Cloud Seeding for Water and Energy in California* is the final report for the White Paper for Cloud Seeding Optimization in California project (contract number 500-99-013), conducted by the U.S. Bureau of Reclamation. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at [www.energy.ca.gov/pier](http://www.energy.ca.gov/pier) or contact the Energy Commission at 916-654-5164.





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## Abstract

The origins of this work trace to a group of professionals from utility companies, water management agencies, and weather modification (WM) scientists. This group was convened in 2005 at the California Energy Commission (Energy Commission) to discuss the current state of WM (cloud seeding) in California and the need to improve that state. WM has been conducted in the Sierra Nevada Mountains to increase water from snowpack since the 1950s, to the benefit of irrigated agriculture, hydroelectric power, recreation, municipal and industrial water users, and water quality. The California Department of Water Resources (DWR) conservative estimates that the combined state seeding projects generate 300,000 to 400,000 acre-feet of water annually. This report examines the current state of winter cloud seeding in general and its practice in California in particular, so as to make recommendations for optimization. Included are a problem statement, WM history, its current state of advancement and obstacles to understanding, benefit/cost ratios achievable versus other water augmentation technologies, and its optimization potential using the latest scientific and technical knowledge. Solutions to problems are offered and evaluated, and recommendations are made for applied research, funding and frameworks toward optimization. The report is intended to inform and provide decision assistance to policy makers in energy, water resources, government, agriculture, environment, recreation, and other sectors of California.

**Keywords:** Weather modification, cloud seeding, snowpack enhancement, precipitation increase, electricity production, water supplies, agriculture, irrigation, recreation



## Executive Summary

Operational weather modification (cloud seeding) has been conducted in California since the early 1950s—one of the longest records of seeding in the world. Cloud seeding has been conducted in many areas, but the most continuous programs have been in winter over the Sierra Nevada. This seeding has been intended to augment snowfall and snowpack. The additional snowpack melts and runs off, providing more water for various uses such as hydroelectric power, agriculture, municipal and industrial needs, recreation, and endangered species habitat. The California Department of Water Resources (DWR) has conservatively estimated a 4 percent annual precipitation increase attributable to the combined state seeding projects.

Seeding of mountain clouds in winter is the most scientifically credible form of intentional large-scale weather modification (WM). This strong conclusion is supported by several professional scientific organizations, including the American Meteorological Society and the World Meteorological Organization. The conclusion is based upon statistical evidence that such seeding, if properly designed and conducted, can augment seasonal precipitation by about 10 percent. A major objective of this report is to survey the current state of the WM field so as to recommend approaches to optimize California's seeding programs. Such optimization might increase the effectiveness of those programs, from the current 4 percent yield toward this goal of 10 percent.

The report describes the following characteristics of winter weather modification:

- Its relevance and need in California.
- Its history and current state.
- Its environmental and health impacts.
- Its downwind effects on precipitation.
- Its costs and potential benefits, relative to other water augmentation technologies.

Past research has demonstrated that cloud seeding poses minimal environmental and health risks and that there is almost no evidence for decreases in precipitation downwind of seeding target areas.

The principal conclusions of this report are that:

- **Cloud seeding is much less expensive than other water augmentation technologies and has large benefit-to-cost ratios. Therefore, seeding is an attractive option to help alleviate water supply problems.** Population growth in California will cause water demands to regularly outstrip water supplies in the near future, especially during inevitable droughts. There is evidence that the current period of atmospheric warming and/or air pollution may be decreasing natural snowfall and, therefore, fresh water supplies. Unless steps are taken, these situations will exacerbate conflicts and instigate litigation over those supplies.

- **Applied research is needed to optimize the effectiveness of operational seeding programs in the state.** This applied research would quantitatively measure cloud seeding effectiveness and identify any impediments to greater effectiveness. The results would lead to changes that can optimize seeding practices. The approach will survey the latest scientific advances in cloud physics, remote sensing, atmospheric science, seeding technologies, and evaluation strategies and then recommend the best courses of action to maximize the contribution of operational cloud seeding programs to the state's water supplies. It is recommended that those programs maintain an applied research component so that the latest scientific and technological advances may be rapidly incorporated on an ongoing basis.

# 1.0 The Impact of Cloud Seeding on California's Water and Energy Situation

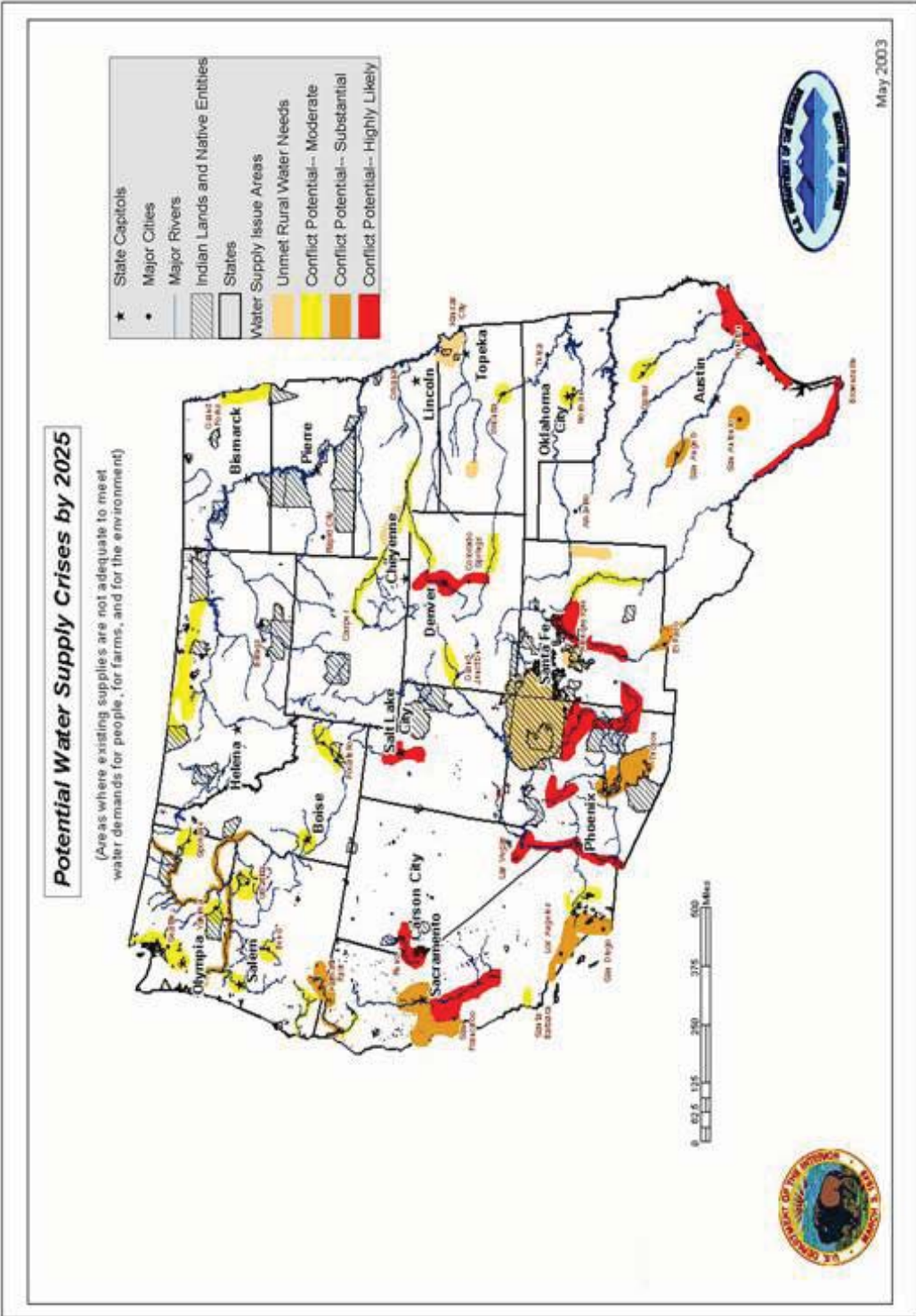
## 1.1. Relevance and Need

California recently suffered an energy crisis, and predictions are that such crises will be repeated unless significant preventative steps are taken. The supply and delivery of electric power in and around California are affected by economic, political, and physical delivery factors. The hydroelectric sector has been adversely impacted by several years of below normal precipitation. In California on average, 15% of electrical power is derived from hydroelectric generation (CEC 2005) and it is the cheapest source of power in the state. The ability of hydroelectric power companies to produce power to meet the needs of California and other western states is heavily dependent on snowpack runoff from the Sierra Nevada and other mountain ranges (primarily those whose snowpack feeds the Columbia and Colorado Rivers). The majority of precipitation that feeds Western hydrological reserves (mainly reservoirs) occurs during the cool season, in the form of snowfall. Fresh water from snowpack melt is also critical for agriculture, recreation, municipal and industrial water users, wildlife and fish habitat, and water quality.

California already experiences fresh water shortages in dry years. Several recent studies project inadequate supplies even in normal years of the near future, primarily because of increasing demands. The [Association of California Water Agencies](#) (ACWA) predicts that the state will be chronically short of water by 2010, unless steps are taken now to improve its water supply system (ACWA 2006). The director of the [California Department of Water Resources](#) (DWR) recently said that the state will need at least two million acre-feet of water *each year* by 2030 to meet the demands of a growing population (Shaw 2006). Similarly, the [Bureau of Reclamation](#) (Reclamation) Water 2025 program states that consumptive use of water in the West continues to grow rapidly, largely because of sustained urban growth (DoI 2003). This situation has already caused major water conflicts, even during normal water supply (non-drought) periods, and is expected to worsen unless significant action is taken. The expected conflict areas identified by the Water 2025 program are shown by Figure 1. Much of the water supply in southern California comes from the Colorado River, whose basin was in a drought from 1999 to 2005. Lake Powell, which serves as a water bank during drought, had April 2005 reservoir storage at 33% of capacity. This was the lowest the lake had been since 1969 (Bureau of Reclamation 2006). Unfortunately, drought is a normal part of the climate cycle in the arid West, and research has shown that far more severe and lengthy droughts have occurred than the one of the last six years (USGS 2004).

Perhaps more disturbingly, there have been widespread declines in western North America's April 1 mountain snowpack since mid-century (Mote et al. 2005). The authors of this investigation point to several climate studies suggesting that this trend will continue and even accelerate. The ski industry is concerned that less snow from warming could seriously impact their operations, and climate models indicate that the lowest-elevation Western resorts would





**Figure 1. Map of expected water conflict areas from Water 2025 website (DoI 2003)**

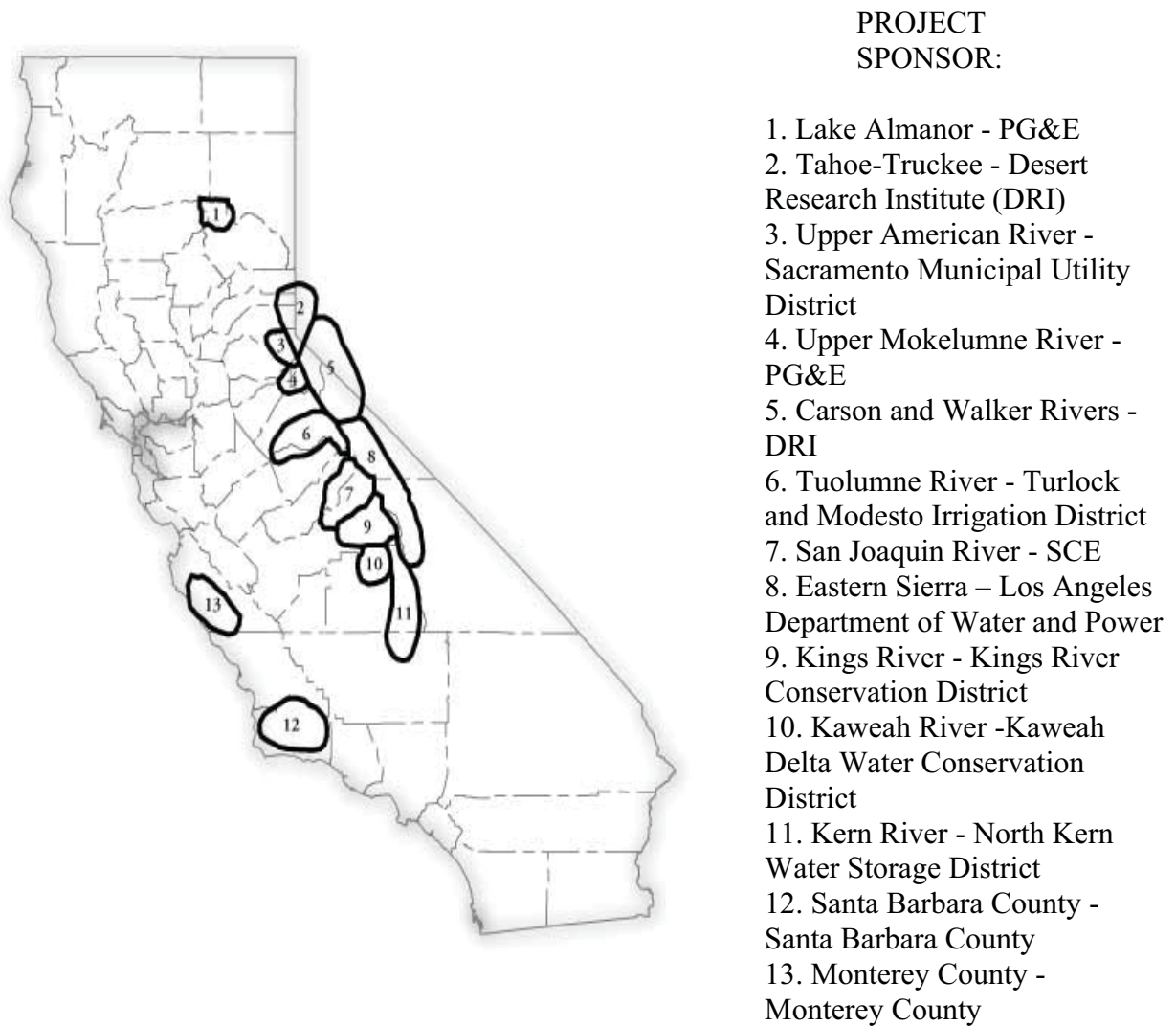
be hurt first (Rocky Mountain News 2005). A recent report (Saunders and Maxwell 2005) declares that climate disruption in the West is already underway and will likely result in more heat, less snowpack, and earlier snowmelt and runoff. Other related impacts could include more evaporation and droughts, less groundwater, and more flood-control releases.

There are several ways to ameliorate the looming crises by augmenting water supplies. One such way is weather modification, commonly called cloud seeding. California is not alone in a recent resurgence of interest in weather modification. On August 25, 2005, the seven Colorado River Basin states addressed a letter to the Secretary of the Interior in which they announced agreement on the development of management strategies for operating Lakes Powell and Mead under low reservoir (drought) conditions. The states said that they wish to work with the Department of the Interior (DoI) to implement a cloud seeding program in the basin. The [Metropolitan Water District of Southern California](#) (MWD) recently added their support for cloud seeding as one way to augment flows in the river (Ryan 2005). Bills were introduced before the United States House of Representatives (HR-2995) and Senate (S-517), proposing a nationwide weather modification research program. Such a program was recommended by a National Research Council (NRC) report on weather modification research (National Research Council 2003), a response to the NRC report by the [Weather Modification Association](#) (WMA) (Orville et al. 2004), and an article on the future of weather modification (List 2004). The [Western States Water Council](#), which is accountable to the [Western Governors' Association](#), made a policy statement in July 2005 endorsing the national program and Congressional bills. The remainder of this paper will discuss the state of weather modification and its potential for augmenting water supplies in California and the West.

## **1.2. Contribution and Limitations of Cloud Seeding Projects**

Cloud seeding has been conducted in California for over 55 years, one of the longest records of operational weather modification anywhere in the world. The earliest program was at the Bishop Creek watershed in the eastern Sierra in 1948, sponsored by the California Electric Power Company, now Southern California Edison (SCE) (Henderson 2004). The Lake Almanor and Mokelumne projects of Pacific Gas and Electric (PG&E) (Marler 1992) and Upper San Joaquin project of SCE have both operated for over fifty years. The Santa Barbara operational precipitation enhancement project (Griffith et al. 2005) began in 1950, with some research phases between 1957–1960 and 1967–1974. Other programs have been operated in Los Angeles and Monterey counties.

Most seeding in California has been intended to increase mountain snowpack for greater hydroelectric power generation, although some of the additional water has been targeted for the state's huge urban and agricultural sectors. The projects have been principally located in the Sierra Nevada and have used ground-based silver iodide as the seeding agent in orographic (mountain) clouds. In a few instances, liquid propane or hygroscopic materials were used for seeding, while aircraft seeding has been done under certain conditions (Henderson 2004). The number of operating projects in California has tended to increase during droughts, up to 20 in 1991, but has leveled off to about 12 or 13. See Figure 2 for a recent project map.



**Figure 2. Map of operational seeding projects in California as of winter 2004–2005, along with project sponsors**

No rigorous, comprehensive study has been made of all California precipitation enhancement projects. Part of the reason for this is the difficulty in selecting suitable *control* basins unaffected by seeding, yet whose natural precipitation or streamflow are highly correlated with the target. A suitable selection facilitates comparison of the control and nearby target area using statistics (Dennis 1980). Unfortunately, wind variations in the Sierra can cause seeding plume transport and spillover of seeding effects into adjoining areas. Target-control comparisons based on the common statistical method of historical regression also assume that the climate has been stable over many decades, a potential problem discussed further in Section 2.3.3. Some studies of individual projects have been made, such as the Kings River project, and have shown “increases in water.” Atmospherics Inc. of Fresno has prepared numerous annual evaluation reports for

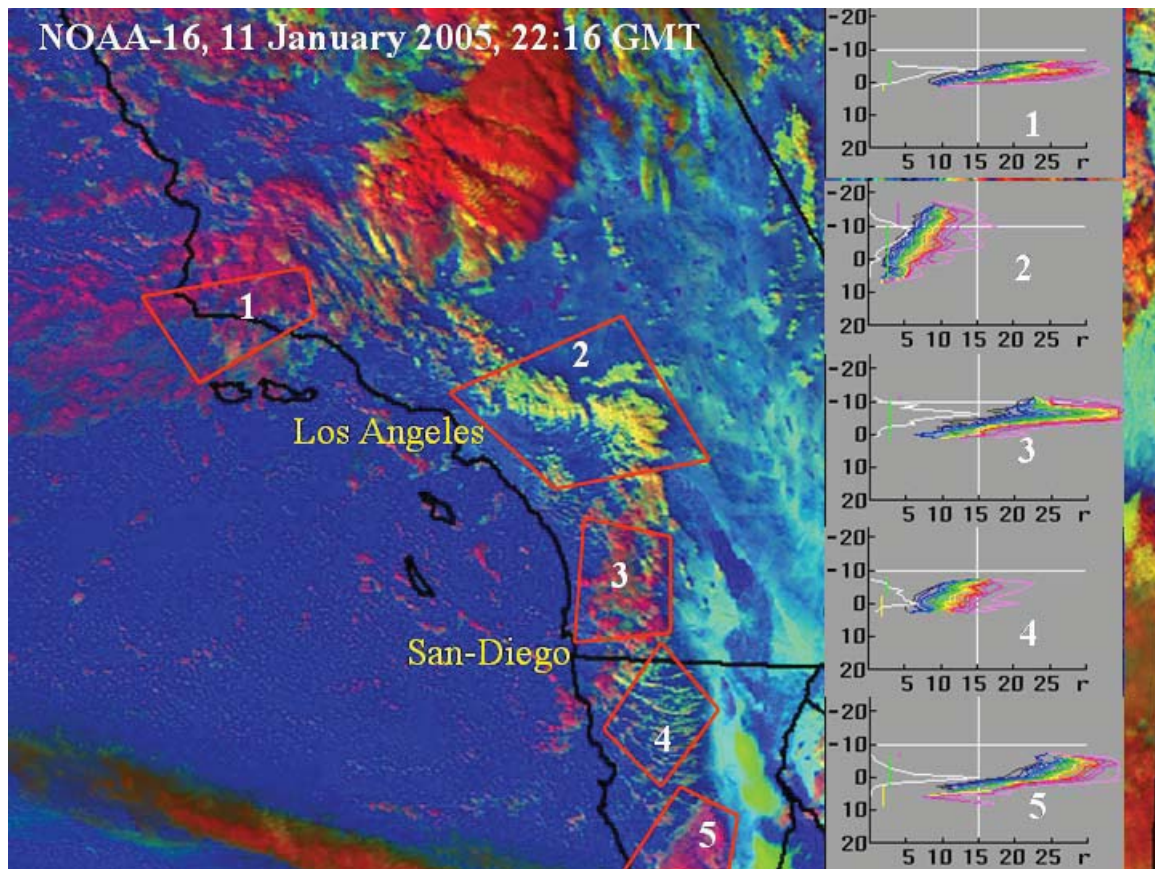
several central Sierra projects. These reports show long-term increases in streamflow via multiple regression analysis, including a six percent increase from 1954–1964 on the Kings River (Henderson 1966; Henderson 2003). Year-by-year analyses of streamflow have shown both positive and negative effects in seeded basins, however, suggesting limitations of this method and the selected control area streams. A study of the Lake Almanor project using a network of precipitation gages in target and control areas found statistically significant increases in precipitation during certain storm types (Mooney and Lunn 1969). This precipitation gage network was costly to operate and has been eliminated from the current project. It has been conservatively estimated that all the California seeding projects generate an additional 4% or 300,000–400,000 acre-feet of water annually (DWR 2005).

### **1.3. Factors Affecting Seeding Effectiveness**

The factors affecting cloud seeding's ability to augment water supplies are manifold and complex, but may be classified as environmental and human. Major environmental factors include: Atmospheric variables like temperature, moisture, wind, stability, cloud physics, and natural nuclei; geographic variables such as topography (slope and aspect), soil moisture and infiltration characteristics, vegetative cover, spatial distribution of the snowpack including exposure to solar radiation, and evapotranspiration. Important human factors include: Seeding technologies like seeding agent formulation and generator output rate; locations, timing and duration of agent release (including airborne or ground-based) relative to the atmospheric variables. The complex and interdependent relationships between these variables make achievement of seeding effectiveness a daunting task, and the modes of success in one locale do not guarantee success in another. Moreover, the climate itself may be changing, casting doubt on whether seeding methods that were effective 20–30 years ago are still so. For example, there is considerable evidence that atmospheric warming will continue (Saunders and Maxwell 2005). Silver iodide, which is the most common cloud seeding agent, is only effective at temperatures of about -5°C or colder, so atmospheric warming could be decreasing the frequency of suitable clouds and, therefore, opportunities for ground-based seeding.

Another possible impact on seeding effectiveness is related to *anthropogenic effects* on clouds. A long-term study (Givati and Rosenfeld 2004) showed precipitation losses over topographic barriers downwind of major coastal urban areas in California amounting to 15%–25% of the annual precipitation. These losses occurred during the twentieth century in increasingly polluted areas, whereas no such trends were observed in similar nearby pristine areas. The authors later investigated (Givati and Rosenfeld 2005) an “orographic enhancement factor” in Israel (ratio of precipitation in inland hilly areas from 500–1000 meters in elevation, to that at upwind coasts and plains) from 1950–2002, segregating seeded and non-seeded days. They found that, as in California, increasing air pollution decreased orographic precipitation; the decreases were of such magnitude as to cancel increases from cloud seeding. Physical evidence of cloud and aerosol changes induced by air pollution downwind of urban areas has been documented by satellite (Rosenfeld 2000; Rosenfeld and Lensky 1998) and aircraft (Axisa et al. 2005) measurements. See Figure 3 for an example of the satellite analyses in California.





**Figure 3. Multi-spectral analysis of satellite image from NOAA-16 polar-orbiting satellite on 11 January 2005. The colors are derived from red-green-blue combinations based on coding various combinations of visible reflectance, temperature, and cloud-top effective radius (size of cloud hydrometeors). Yellow-white areas are clouds composed of many smaller hydrometeors, typical of continental clouds that are less likely to produce precipitation by the coalescence process. Reddish areas are clouds that have more maritime pristine structure, with fewer but larger hydrometeors, thereby more likely to generate precipitation. Plots on the right correspond to the numbered areas on the satellite image and show sizes of particles or effective radius  $r$  (on x-axis, in micrometers) vs. temperature in  $^{\circ}\text{C}$  (on y-axis). Note that area 2, downwind of Los Angeles, has much smaller particles  $r$  than in other more pristine areas. Source: Daniel Rosenfeld, Hebrew University of Jerusalem, presented at 16th Conference on Planned and Inadvertent Weather Modification, San Diego, California, January 2005.**

Because of the ramifications of the anthropogenic findings for hydroelectric power generation in California, studies of how aerosols affect clouds and precipitation in the Sierra Nevada have been continued within the Suppression of Precipitation (SUPRECIP) Experiment. The SUPRECIP, which is being funded by the Public Interest Energy Research (PIER) Program of the California Energy Commission (Energy Commission), had major field campaigns in the winters of 2005 and 2006. In 2006, extensive measurements were made in Sierra clouds with a well-equipped Cheyenne-2 cloud physics aircraft and a Cessna 340 (mostly cloud-base) aerosol aircraft. Measurements were made in deep, mostly glaciated clouds, and in relatively shallow clouds whose liquid water was mostly supercooled (colder than the freezing point). Analysis of the unique SUPRECIP data set is underway, toward the goal of documenting the effects of

aerosols on Sierra clouds and precipitation. These data should also be a valuable resource for optimizing cloud seeding in the region.

The atmospheric effects of long-term warming and urban/industrial air pollution are only two possible influences on seeding effectiveness. Since the 1950s there have been *variations in seeding materials and technologies*. Some seeding generator locations have also changed. Therefore records of the seeding operators must be preserved and examined for such changes and an assessment made of their possible consequences. Of course other influences, related or unrelated to the ones cited above, may play a role.



## 2.0 What Current Knowledge and Future Applied Research Can Do to Optimize Cloud Seeding

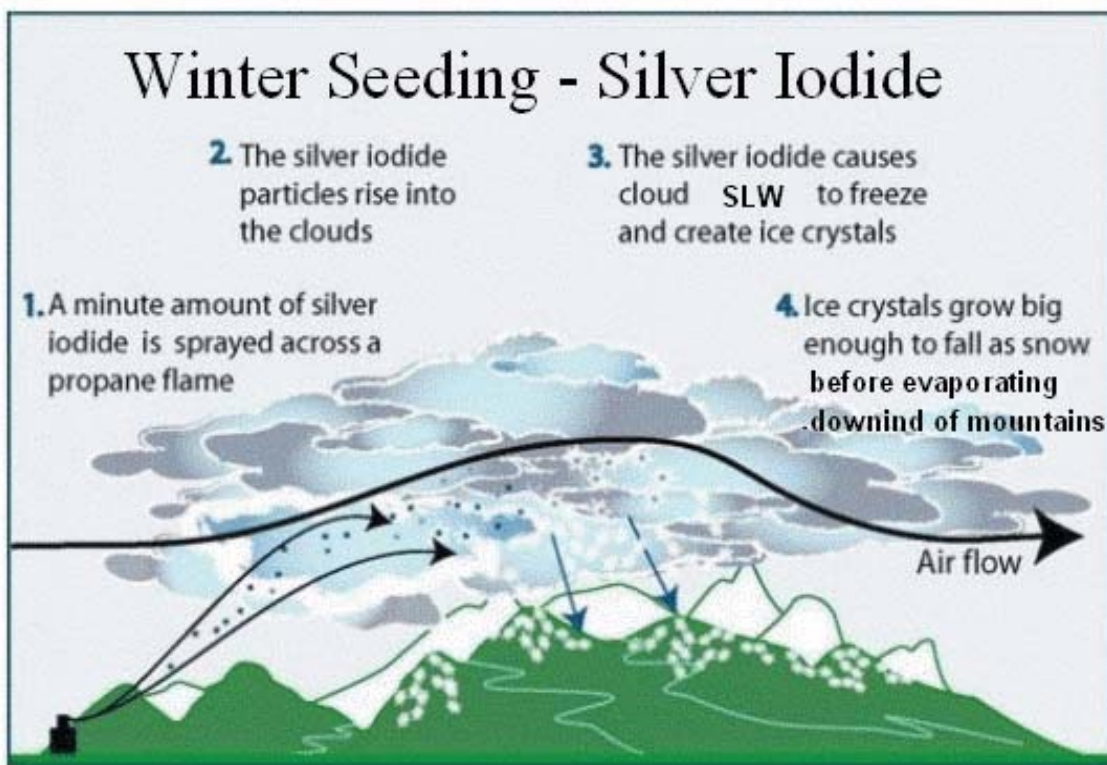
### 2.1. What is cloud seeding?

The primary type of seeding in California has been in cold-season orographic clouds, so that type will be the principal focus here. Seeding to suppress hail and disperse fog is routinely conducted in other states. According to the [North American Interstate Weather Modification Council](#), there are presently operational programs in 11 of the 17 Western states. Precipitation enhancement of warm-season convective clouds with hygroscopic materials (substances like salt that take up atmospheric water) has shown promise, but has not been used much in California.

Cold-season orographic clouds form as moist air flowing from the Pacific begins to rise rapidly as it reaches the western (windward) side of the Sierra Nevada. This rise results in cooling, condensation and, often, precipitation as either rain or snow. In many instances within these clouds, water droplets remain as liquid at temperatures below the freezing point (32°F). Such droplets make up *supercooled liquid water* (SLW) clouds, the presence of which leads to aircraft icing. Only a small fraction of SLW droplets freeze into ice crystals, usually through interaction with tiny wind-blown particles called ice nuclei (IN). These crystals then grow rapidly at the expense of the much more numerous SLW droplets, and can attain sufficient size to fall to the ground as snowflakes. While natural IN exist in nature, their effectiveness is limited unless SLW cloud temperatures are relatively cold. Silver iodide and other seeding agents can create ice crystals at significantly warmer temperatures. Cloud seeding can thus initiate snowfall within this "temperature window of opportunity," when nature is ineffective at doing so.

By far the most common seeding agent in the history of weather modification has been silver iodide (AgI), released as a fine smoke. This compound has a crystalline structure nearly identical to ice, effectively providing IN that interact with water vapor or SLW droplets to form tiny ice crystals. Figure 4 illustrates how AgI seeding from ground generators works. The most effective AgI nucleants can begin producing ice crystals at temperatures colder than about -5°C. An alternative is to chill the air sufficiently so that the SLW droplets freeze *without* nuclei. This





**Figure 4. Basic silver iodide seeding process from ground generators**

chilling is accomplished through introduction of dry ice or expansion of liquid propane (LP) into a gas. Liquid propane can begin ice crystal formation at  $-1^{\circ}\text{C}$  or colder, expanding the temperature window of opportunity. Water vapor and SLW generally increase with warmer temperatures, so SLW is frequently more abundant within this expanded window from  $-1^{\circ}\text{C}$  to  $-5^{\circ}\text{C}$ . Therefore, much SLW is not converted to precipitation naturally and passes downwind of mountain crests, where it evaporates. Seeding agents that are effective in this warmer, expanded temperature window are consequently attractive, as recognized in the design of a major LP seeding experiment (Reynolds 1996) in the Northern Sierra Nevada. Whatever their initiation process, seeded ice crystals, like their natural counterparts, grow rapidly at the expense of the SLW droplets.

The foregoing discussion deals with the cloud microphysics associated with seeding. Such microphysical conditions depend in complicated ways on atmospheric dynamics and thermodynamics. All these conditions are intimately linked with atmospheric motions on a vast range of scales, from planetary scale circulations to synoptic ("weather map") scales, to storm scales to small-scale turbulent motions. Some understanding of all these phenomena is necessary to develop a *conceptual model* of the atmosphere, on which effective seeding approaches depend. This conceptual model is continually revised as the atmosphere is studied and new knowledge attained.

### **2.1.1. Does Seeding Work and How Much More Water Can It Produce?**

There is evidence that seeding of orographic clouds to augment snowfall is more effective than all other types of weather modification (except for cold fog suppression, which certainly works). This claim is supported by a policy statement of the [American Meteorological Society](#) (AMS) (AMS 1998), a weather modification status statement of the [World Meteorological Organization](#), the NRC report (NRC 2003), and the WMA (Orville et al. 2004). The AMS further states that there is statistical evidence that such seeding can produce seasonal precipitation increases of about 10%.

The California DWR (DWR 2005) estimates that an additional 300,000 to 400,000 acre-feet of water could potentially be produced annually by more and improved cloud seeding in California. This increased amount of water would come at a cost of about \$19 per acre-foot. Many of the best prospects for additional weather modification water increases are in the Sacramento River basin, in watersheds that are not presently seeded. Most of the southern Sierra basins in the San Joaquin River and Tulare Lake regions are already seeded (Figure 2). With the exception of the upper Trinity River watershed and perhaps the Russian River, there is little new potential in the North Coast region, since not much extra runoff could be captured because of limited storage capacity (DWR 2005). There is also potential to increase water production by improving the effectiveness of existing seeding projects.

The main question is how best to achieve additional water through weather modification. The physical mechanisms described in Section 2.1 are well documented (Dennis 1980). Although the NRC and WMA have some disagreements, they concur that winter orographic cloud seeding is promising for the aforementioned increases and that there is a need for a fully randomized statistical weather modification program to build on existing operational projects (Garstang et al. 2005). This program would have strong observational and computer modeling components, and incorporate the latest science and technology. Most importantly, the program would increase confidence in estimation of attainable seasonal snow water equivalent increases from cloud seeding.

Cloud seeding should not be viewed as a drought “fix” to be conducted only during dry periods, since seeding opportunities are less frequent in such periods. Seeding *every year*, however, can augment surface and ground water storage to increase average supplies, helping alleviate the adverse impacts of drought. Weather modification should be viewed as “one tool in the toolbox” of water resource management.

## **2.2. The State of Weather Modification and its Capabilities**

### **2.2.1. Current Knowledge and Remaining Challenges**

Success in cloud seeding requires substantial knowledge of the physical processes in natural clouds and how seeding materials change those processes to augment precipitation. There have been two major research projects related to cloud seeding in California. The larger effort was the Sierra Cooperative Pilot Project (SCPP), which was conducted by Reclamation and the states of California and Nevada between 1977 and 1987. The SCPP (Reynolds and Arnett 1986) focused on physical mechanisms affecting Sierra Nevada clouds, so that sound cloud seeding

technologies could be developed. Ground-based and airborne silver iodide seeding was done, along with the release of tracer materials to assess the transport and diffusion (T&D) of seeded plumes (Section 2.3.1 below). Major findings were: Sierra Nevada storms often have rapidly changing phases that affect seedability; a low-level barrier jet stream frequently complicates T&D and targeting of seeding materials; clouds are frequently efficient *natural* snowfall producers because of a process known as ice multiplication; and most of the SLW that is needed for seeding to be effective is within 3000 feet of the ground, at temperatures warmer than  $-10^{\circ}\text{C}$  (Marwitz 1987; Reynolds 1989; Rangno 1986).

The second project, the Lake Oroville Runoff Enhancement Project (LOREP), was performed in the northern Sierra near Beckwourth, California, from 1991–1994. The LOREP was the first project in the United States to use LP gas as the seeding agent. The choice of LP was based on findings of SLW existence at relatively warm temperatures, since LP can be more effective at those temperatures (Section 2.1). Seeding plumes were successfully tracked using tracer gases, and ice crystals within plumes were also studied. The LOREP was suspended after three years (short of the intended five years) because T&D caused problems in targeting seeded ice crystals, necessitating a design change. The shorter duration also precluded statistically significant results from the randomized part of the seeding experiment. There has been no LP experimentation in the Sierra since the LOREP. Nevertheless, the existence of significant SLW when temperatures were warmer than  $-4^{\circ}\text{C}$  was confirmed to occur about 80% of the time (Reynolds 1996).

Several review articles (Rangno 1986; Reynolds 1988; Super 1990) have stated that achieving adequate T&D for seeding SLW regions is probably the most difficult problem facing winter orographic cloud seeding. This was recognized as a still-fundamental problem in a more recent review article (Bruitjes 1999) and it remains an issue in California's operational programs, although chemical tracer experiments and plume dispersion models have improved understanding. First, seeding materials must be transported in adequate concentrations to cloud regions with sufficient SLW and proper temperatures. If that is achieved, the materials must then generate ice crystals in sufficient concentrations in regions where the crystals can grow and fall out, producing significant snow precipitation in the desired target area. If any processes in this physical chain of events are not satisfied, the seeding will not significantly increase precipitation in the target. Tracer experiments have been conducted by PG&E, SCE, and the Desert Research Institute (DRI). These experiments have revealed some of the complexities of targeting seeding materials, given the complicated wind fields that occur within the Sierra Nevada (Figure 5). Local wind steering by valleys and ridges, flow blockages by mountain peaks, and other dynamic meteorological effects can shift seeding material and effects to areas outside the target. Sometimes the shifts can be toward control areas, adversely affecting evaluation efforts. Use of high-altitude ground-seeding devices, at least halfway up the

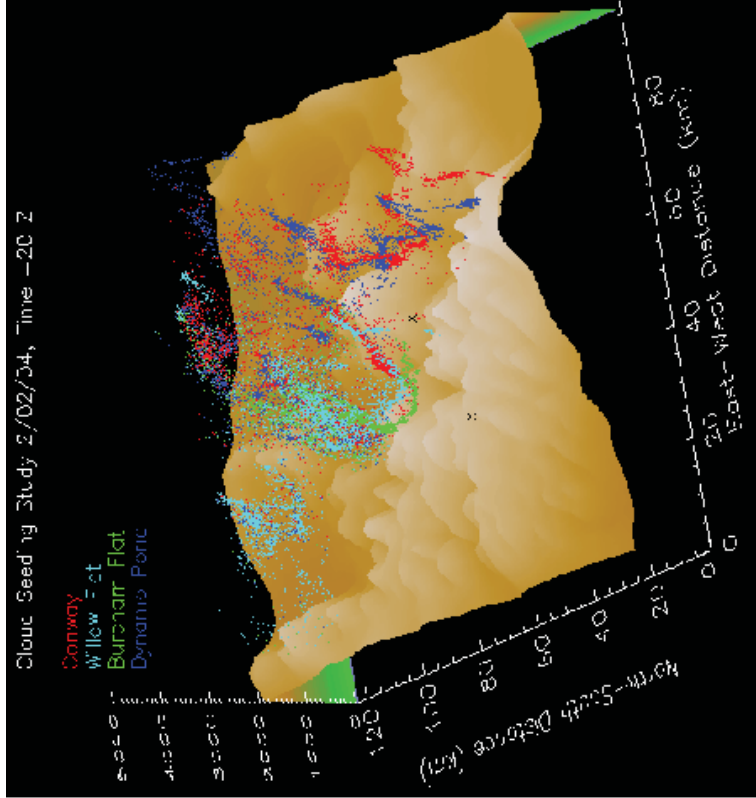
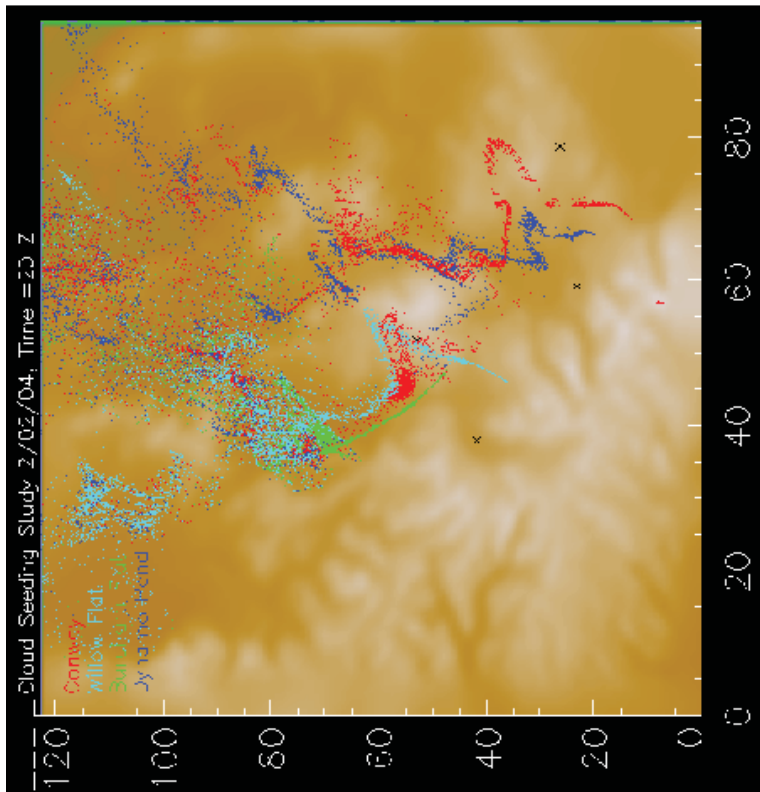


Figure 5. Plan view (left) and 3-D perspective view (right) of Walker River Basin from the southwest. Shown are simulated seeded particle plumes from four generator sites (each with a different color). The simulations were done with a Desert Research Institute dispersion model. The Walker Basin straddles the California/Nevada border and is east of the Sierra Nevada, which is outlined by the white areas (Huggins et al. 2005a).



windward slope, substantially reduces targeting uncertainties (Holroyd et al. 1988). In mountain ranges with extensive wilderness areas, siting of those devices can be problematic, because they are not allowed in such areas.

Knowledge of cloud seeding will continue to advance through basic and applied research, and through seeding or related hydrometeorological experiments. California can benefit from ongoing research projects; particularly those being conducted in the state. An excellent example is the [Hydrometeorological Testbed](#) (HMT) program, expected to be conducted in the American River Basin from 2006–2011 (NOAA 2006). This basin overlaps or is near to existing weather modification programs in the Upper American, Tahoe-Truckee, Carson-Walker, and Upper Mokelumne Basins. The HMT program will deploy transportable and mobile scanning precipitation radars, wind profiling radars, precipitation profiling radars, and global positioning system (GPS) sensors for measuring precipitable water vapor. Additional instruments will include precipitation gauges, raindrop disdrometers, surface meteorological stations, soil moisture/temperature probes, radiosondes, and stream level loggers. The HMT will provide a wealth of data important to weather modification in California, and it is advisable that future efforts to optimize operational seeding programs establish a collaborative and synergistic data exchange with the HMT program and others like it. The HMT, however, will not involve cloud seeding and so cannot provide answers to all the remaining questions facing weather modification in California and elsewhere.

### **2.2.2. Are There Any Adverse Impacts?**

Questions about potential unintended impacts from cloud seeding have been raised and addressed throughout the history of weather modification. Common concerns are: (1) downwind effects—that is, enhancing precipitation in one area at the expense of those downwind (“Robbing Peter to pay Paul” or “cloud rustling”), (2) long-term environmental or health effects of seeding materials, and (3) consequences of additional snow.

As for the first concern, evidence does not show that seeding clouds with silver iodide causes a decrease in downwind precipitation; in fact, sometimes there may be an increase as far as 100 miles downwind of the target area (Bureau of Reclamation 1977; Harris 1981). The amount of atmospheric moisture passing over a mountain barrier that is converted to precipitation is usually 10% or less of the total water budget. If this natural precipitation is increased 10% by cloud seeding, only 1% of the original atmospheric moisture supply is depleted by seeding. Moreover, winter cloud seeding is conducted on the upwind side of mountain ranges. These clouds usually dissipate on the downwind or lee side of the range, a natural effect called the “rain shadow.” This is why areas downwind of mountains, like Eastern Colorado and Nevada, are much drier than upwind areas. So the atmospheric moisture supply on the downwind side of mountain ranges will not likely precipitate anyway (unless aided by weather modification).

Regarding the second concern, Reclamation has studied environmental and health impacts extensively (Bureau of Reclamation 1977; Harris 1981; Howell 1977). The toxicity of silver and silver compounds (from silver iodide) was shown to be of low order. According to Reclamation, the small amounts of silver used in cloud seeding are 100 times less than industry emissions into the atmosphere in many parts of the country or individual exposure from tooth fillings.

Accumulations in the soil, vegetation, and surface runoff have not been large enough to measure above natural background (Klein 1978). A 2004 study for Snowy Hydro Limited in Australia confirmed these earlier findings. The expansion of LP as a gas is another possible seeding method. Regarding the flammability of propane released from dispensers (Vardiman et al. 1971), it was shown that it was necessary to bring the ignition source to within four feet of the dispenser nozzle to cause the propane plume to burn under very light winds. A modest increase in wind speed would blow out the flame. It was further noted that, "Propane is a colorless, odorless, hydrocarbon that is harmless to plant and animal life. The quantities used in seeding are so small, 0.75 lb per minute from each dispenser, that there is no accumulation leading to a pollution problem." Another study (Super and Heimbach 2005a) noted that "There is a great deal of propane (C<sub>3</sub>H<sub>8</sub>) and butane (C<sub>4</sub>H<sub>10</sub>), another hydrocarbon, being released by human activities at a scale far larger than for propane seeding. Propane does not present an environmental hazard because of its rapid oxidative degradation. Although technically a greenhouse gas, its approximate one month lifetime in the atmosphere is too short to function in this manner. In contrast, chlorofluorocarbons (CFCs) have atmospheric lifetimes in the range of 60–500 yrs."

As for the third concern, the consequences of additional snow, the SSCP Environmental Assessment report (Harris 1981) investigated the impacts of an assumed weather modification-induced precipitation increase of 5%–7.5% on weather elements, hydrologic and physiographic phenomena, plant and animal communities, the human environment, and land and water resource use. The report concluded that there would be no significant impact on these environmental sectors. The percentage increases from weather modification are much smaller than inter-annual variability of natural precipitation. Furthermore, all California operating projects have suspension criteria designed to stop cloud seeding anytime there is a flood threat. All projects employ meteorologists who monitor current and projected weather conditions. Additionally, water management personnel from sponsoring companies monitor streamflow and reservoir storage. The combined interdisciplinary inputs about flood potential are considered, and conditions are compared against suspension criteria in advance of any potential flood-producing storms. Moreover, the types of storms that produce floods in California are almost always too warm for effective silver iodide seeding (Byron Marler, PG&E, personal communication). Although weather modification increases are small compared to natural precipitation variability, one can anticipate some concerns about snow removal from roads and snow loading on roofs.

Finally, some have questioned the notion of "interfering with nature" through weather modification. These questions often ignore the fact that human activities have caused *inadvertent* weather modification for many centuries. The NRC report (NRC 2003) states that "there is ample evidence that inadvertent weather and global climate modification (e.g., greenhouse gases affecting global temperatures and anthropogenic aerosols affecting cloud properties) is a reality." Even the simple act of cultivating a farm field will alter local climate. *Intentional* weather modification, particularly of the form practiced in winter seeding, alters the environment far less than the accumulated effects of *inadvertent* weather modification. Indeed,

cloud seeding in California may have been partially compensating for precipitation losses from the inadvertent weather modification brought on by air pollution.

### **2.2.3. Anticipated Developments and their Relevance to California**

The foregoing information points to a need for applied weather modification research that can be integrated into California's operating weather modification programs rapidly and effectively, so that those programs may be optimized. Therefore, anticipated developments in the next few years may be classified as unfolding on two fronts – applied research and programmatic support for that research.

The most recent weather modification research effort is Reclamation's Weather Damage Modification Program (WDMP) (Hunter et al. 2005). The WDMP was begun in late 2002 and was the first federally supported research program in over a decade. Although federal funds were limited (\$2 million), they were matched by funds from several participating states. Cost leveraging was also achieved by "piggy-backing" the research on operational weather modification projects already being conducted by those states. The WDMP concluded in 2006, but most states had already finished their research, including the orographic seeding states of Utah, Colorado, and Nevada. In Utah, a randomized experiment using LP was carried out on the Wasatch Plateau (Super and Heimbach 2005b). Routine targeting of the seeded plume was already assured by prior T&D studies. Seeding dispensers were fully automated, with experimental units (EUs, seeding or placebo) initiated by the detection of SLW cloud with an icing sensor. There was a 25% increase in precipitation of seeded EUs versus non-seeded, and seeding generated sufficient ice crystal concentrations to produce at least 0.01 inch per hour additional precipitation. Given measured SLW frequency, this would yield an estimated 8% increase in seasonal precipitation. This percentage is close to that given in the AMS policy statement on weather modification (AMS 1998).

The Nevada WDMP was in the Sierra Nevada near the California border, and so its results are highly relevant here. Major components were as follows:

1. *Physical and chemical snowpack analyses* from the Walker and Truckee/Tahoe Basins using minute amounts of silver, cesium, rubidium, and other chemicals to determine and distinguish targeting by seeded plumes from ground and aircraft sources (Huggins et al. 2005a) Results show routine targeting by high-elevation ground generators, and less frequent targeting by aircraft seeding. There was no correlation between snow density and silver content.
2. *Modeling studies* - A particle dispersion model integrated with a numerical cloud model was used to predict seeded plume locations, for comparison to the trace chemical analyses and for evaluating seeding generator placement (Huggins et al. 2005b). Results show complex and rapidly changing plumes as they move in the rugged terrain of the Sierra Nevada and downwind regions (Figure 5). The model also showed contamination in the Tahoe and Nevada Carson target areas from upwind operational seeding projects. Mountain-induced atmospheric gravity waves, which can dramatically affect T&D, were also predicted.

3. *Hydrologic modeling* - A hydrologic model was revised to assess the impact of an assumed 10% precipitation increase in the Walker Basin. Resulting runoff percentages varied from 65% to 95% of this added precipitation, depending on soil and vegetation characteristics in the sub-basins.
4. *Aircraft microphysical measurements* - Initial findings show a general inability to document seeding effects with aircraft. This outcome may be the result of numerous cloud physics aircraft flights over downwind target areas, where evaporation/sublimation of seeding-induced ice particles may be occurring. Previous investigations, however, have documented seeding effects with aircraft (McGurty 1999). Aircraft and radiometer measurements were used to validate the cloud model predictions, and showed that the extension of SLW into regions downwind of the Sierra Nevada was under-predicted by the model. The overall findings of the Nevada WDMP revealed that model targeting can be verified by the presence of seeding material in the snowpack, that ice nucleation rather than just scavenging (Section 2.3.1) has been verified by dual-tracer experiments, and that the potential for a quantitative evaluation of seeding effects may be realized through chemical and physical measurements of snowfall.

The NRC report on weather modification (NRC 2003) points out a paradox: operational WM has continued unabated, with activities in 24 countries and eleven U.S. states, despite inadequate understanding of critical atmospheric processes, which in turn has led to a scarcity of predictable, detectable, and verifiable results. This paradox may be partly explained by the perception among sponsors that potential rewards are greater than the relatively low financial investment required to practice operational weather modification. The NRC further recognizes that there have been major improvements over the last few decades in computing power and modeling, observational technologies, statistical methods, and new seeding materials. But these improvements have not been satisfactorily realized in weather modification, according to the council, because of *lack of funding support* for this field of science in the United States. For example, compared to 30 years ago, there has been about a 30-fold reduction in inflation-adjusted dollars being spent on cloud seeding research in the United States. In the last three years, less than \$500,000 has been directed at research topics that are specific to California.

This is where the Energy Commission's PIER program can help. PIER receives funds from California utilities (gas, electric, telephone, cable) via a small charge on each rate payer's monthly bill. In turn, PIER funds research for the public good of California and its ratepayers. SCE and PG&E have been working with PIER representatives, toward establishing a coordinated PIER research program on the topic of optimizing cloud seeding technologies for California. There is also potential to match PIER research funds with federal research funds for work on cloud seeding technology.

### **2.3. Possible Methods and Evaluation Framework**

The methods discussed in this section are classified according to the weather modification issues and developments presented above. Each subsection describes how the method



addresses those issues or developments, as well as the potential strengths and weaknesses of each approach.

### **2.3.1. Transport and Diffusion of Seeding Materials - Modeling and Observations**

As submitted above, T&D of seeding materials is widely regarded as the biggest obstacle to their effectiveness. The complex and dependent physical chain of events must occur in the proper sequence and locations, with sufficient concentrations of effective seeding materials, to produce desired precipitation augmentation. Assessment of the ability of seeding to meet these criteria can be done through direct observations or possibly through modeling.

As related in the NRC report (NRC 2003), computer modeling has seen great advances in the last two to three decades, and weather modification should capitalize on its use. Three-dimensional cloud models capable of simulating T&D and cloud microphysics related to seeding effects have already been used in research. Examples include experiments in Utah (Heimbach et al. 1997), the Nevada WDMP (Huggins et al. 2005b), Colorado WDMP (Busto et al. 2005), and a feasibility study for a new Wyoming cloud seeding pilot project (Jensen et al. 2005). Such modeling can be used to predict seeded plume T&D for optimum placement of seeding generators, as well as verification of seeding effect (precipitation enhancement). Although there have been significant advances in modeling, most investigators agree that models are not currently sophisticated enough to accurately simulate all relevant cloud processes, and therefore they should not be the only tools used in prediction and verification. This is where direct observations can help.

Direct physical measurements have been made in weather modification for many years. An important type of such measurements has been tracers. Examples of tracers are gases such as sulfur hexafluoride ( $\text{SF}_6$ ) or chemicals like silver, indium, cesium, or rubidium. The chemicals are often released simultaneously with aircraft or ground released seeding materials, and can be detected downwind of those sources. The silver content from the seeding material itself ( $\text{AgI}$ ) has frequently been used as a tracer. This silver can either be scavenged from clouds by natural (not seeded) precipitation, or it can be deposited in the snowpack as a result of ice nucleation, growth and fallout. Therefore, comparative use of the other chemicals that can be scavenged, but do not have ice-nucleating properties, can provide strong evidence that the seeding plume produced additional precipitation over the target area (Warburton et al. 1995a). Failure to measure silver in snow at greater than natural background levels, however, indicates that a silver iodide seeding plume did not interact with clouds and precipitation in the target area in such a way to make seeding effective. Other physical measurements may be used to distinguish seeded from natural ice particles. For example, the sizes and habits of those particles can be measured by electronic probes or direct capture. Also, the density of various layers in the snowpack corresponding to seeded or unseeded periods can be compared for any differences. A 1994 SCE research project (McGurty 1999) measured density increases in seeded snow layers to estimate a minimum 8% increase in snow water from seeding. More such research could enhance the physical basis of project evaluation.

One of the greatest uncertainties in both modeling and physical measurement of seeded plumes is the concentration of ice crystals produced by seeding. It is believed that concentrations

exceeding 20 crystals per liter of air are required to produce significant precipitation rates (Ludlam 1955; Super 2005a). Assessment of crystal concentrations *at a given location* in the target area depends on (a) the plume concentrations at a single time, and (b) the spatial meander of the plume with time. As seen from Figure 5, both (a) and (b) can be highly variable. More research into ice nucleants, both natural and seeded, is needed to address these uncertainties.

### **2.3.2. Seeding Technologies and Effectiveness**

The principal seeding methods have used AgI, hygroscopic particles, dry ice, and LP. These first three can be dispersed from ground generators or aircraft. Hygroscopic particles and dry ice have not been used much in California, and the former is mainly employed in warm-season seeding of convective clouds. Therefore the focus will be on AgI, LP, and their methods of delivery. The effects of these two methods on cloud microphysics were discussed in Section 2.1, so the following will address equipment and related logistics.

Aircraft seeding with AgI can be done through combustion in place or via droppable flares. Because of aircraft movement, the result is a “line source” of AgI, which combined with atmospheric motions and ice particle fall speeds, produces a “curtain” of seeding effects. The shape and extent of this curtain are highly determined by T&D that is in turn controlled by atmospheric winds, turbulence, and cloud microphysics. Whether this curtain routinely envelops the target area to produce desired precipitation amounts has not been conclusively shown (Deshler et al. 1990), so more research is needed in this area. Furthermore, since the bulk of SLW is frequently confined to the lowest 3000 feet above the surface, it presents a problem for aircraft seeding. Safety restrictions frequently prohibit aircraft operation that close to mountainous terrain. The Federal Aviation Administration (FAA) mandates a minimum flight level over mountains of 2,000 feet above the highest terrain within a horizontal distance of four nautical miles, although in special circumstances a waiver permits a clearance of 1,000 feet. Icing conditions, especially during darkness, add to the concern. There may be some mountain barriers where aircraft seeding might be worth consideration, particularly where ground seeding is not feasible (e.g., in wilderness areas). Such mountains should be relatively isolated so aircraft could safely descend below the freezing level when airframe icing becomes excessive, or where aircraft could remain well upwind where exposure to icing would be limited. Aircraft seeding is substantially more expensive than ground seeding, so the value of water augmentation would need to be high enough to justify such an option.

Seeding from the ground has been accomplished in the Sierra Nevada principally through AgI generators. At least one project in the California coastal mountains seeds from the ground using a rack with end-burning AgI flares. There have been experiments using LP dispensers (Section 2.2.1). All three devices may be remotely controlled, allowing them to be located at high altitudes that are not routinely accessible by operators and technicians. High altitude, remotely controlled devices allow fast response to changing storm conditions, and increase the chance of seeded plumes reaching the proper temperature and SLW regions of orographic clouds. These devices are less common than their manually operated counterparts, because of increased cost and operational complexity; however, some California and Nevada projects have used them

exclusively. Remote controlled AgI generators are more costly and complex than remote controlled LP dispensers.

Whatever types of seeding devices are used, *it is critical that they be sited so they provide adequate and routine coverage of the target area.* This is no simple task, as it must take into account highly variable meteorological conditions during storms; see the T&D discussion in Section 2.2.1. Nevertheless, earlier studies (Super 1990; Super 1974; Super and Heimbach 1983; Super and Heimbach 1988; Griffith 1996) indicate that seeded plume widths are less than 30 degrees. More measurements of the variations of ice crystal concentrations within seeded plumes are needed (Super and Boe 1988; Super and Heimbach 1983). Even if such measurements are lacking, it is prudent to space generators/dispensers close enough across the wind to produce *overlapping* plumes and sufficient crystal mass for significant snowfall increases (20 crystals per liter minimum requirement, Section 2.3.1). These instrument sitings and configurations are among the most important ways to optimize seeding. Operational projects should assess these issues and make changes as needed. Much more detail on SLW availability, T&D, and generator siting may be found in a recent seeding feasibility study (Super and Heimbach 2005c).

Finally, AgI generators should be able to adjust and measure solution flow rate and flame temperature, to ensure that seeding is occurring as planned. Likewise for LP dispensers, propane flow rate and temperature downstream of the expansion nozzle should be monitored. The search for optimum chemistry formulations, burners, and particle sizes from generators should continue.

### **2.3.3. Evaluation Techniques**

Scientific evaluation of seeding effects adds cost to operational seeding programs, and therefore has not been commonly pursued as part of those programs. There have been several research projects in which evaluation of effects was the primary objective. The main goal here should be to optimize seeding methods through applied research. This research should demonstrate that seeding materials are producing the desired precipitation increases in the target area. The three primary evaluation methods may be categorized as physical, modeling, and statistical.

*Physical Techniques.* The approaches in this category involve either remote or *in situ* measurements of seeded plumes, their effects on precipitation, or other atmospheric parameters related to cloud seeding. To measure seeded plumes and their effects on precipitation, aircraft sampling and trace chemical analyses of snow have been used. Examples include single and dual tracer techniques, and combined physical and chemical methods (Chai et al. 1993; McGurty 1999; Warburton et al. 1995b; Warburton et al. 1996). An example of measuring seeding-related parameters would be microwave radiometer (remote sensing) and aircraft or ground (*in situ*) measurements of SLW. Satellite sensors continue to be improved and techniques for monitoring cloud hydrometeors, such as the one used to produce Figure 3, will certainly contribute to weather modification-related knowledge. Satellites have the advantage of a much wider sampling area than other instruments, and may be able to measure cloud SLW in certain cases. Radar has also been used to track seeding plumes (Martner et al. 1992; Reinking et al. 1999). There is a consensus among scientific organizations (NRC 2003; AMS 1998; WMO 2004) that physical measurements are crucial to evaluations, since they are needed to

verify and quantify the physical chain of events required for successful seeding. Monitoring of natural ambient conditions such as SLW and temperature *in advance* of any seeding is highly desirable, since it would set a baseline for evaluating seeding feasibility and eventual seeding effects.

*Modeling Techniques.* This approach has gained popularity in the last decade, fueled by increases in computing power. Recent examples include the Colorado and Nevada WDMP experiments and the Wyoming pilot project (Section 2.3.1). These projects have used sophisticated three-dimensional numerical cloud models coupled with dispersion models. These models predict seeded plume dispersion in mountainous terrain, which have been used for targeting assessment and generator placement as well as evaluation of seeding effects. The output of such models is exemplified in Figure 5. Hydrologic models have been used to estimate streamflows resulting from assumed seeding-induced snowpack increases. Modeling has seen considerable improvement in physical simulation, theory, speed, sophistication, and accuracy, as acknowledged in the NRC report. Nevertheless, model simulations are not presently accurate enough to distinguish seeded from natural precipitation or streamflow, and therefore models are generally used for guidance purposes only. Use of models in conjunction with physical measurements and statistical analyses can be a very useful integrated approach, however. There are some instances of modeling results comparing favorably with physical sampling (Holroyd et al. 1995).

*Statistical Techniques.* Statistics have been the most common and long-standing tools to assess seeding effects, having been used almost since the inception of weather modification itself. The task has proven formidable, since precipitation augmentation from seeding is small compared to the natural variability of precipitation. The problem is exacerbated because it is difficult even to predict the behavior of natural clouds. The statistical approach has largely consisted of two types: historical target-control regression, and randomized seeding trials. The former attempts to compare precipitation from an area assumed to be targeted by seeding and from a nearby but similar area unaffected by seeding (similar in geography, altitude, etc.). This approach requires a suitably long duration of observations in both the seeded and non-seeded areas during the historical period, to establish a relationship for predicting natural target precipitation during the operational seeding period. Departures between predicted and observed target amounts can then be statistically tested. The comparison can be between variables such as snow water and runoff, as well as precipitation. A long duration, perhaps 10 years or more, is required to achieve stable, statistically significant results (as exemplified by some Kings River investigations (Henderson 1966; Henderson 2003)). The main assumption here is that the relationship between natural precipitation in the target and control areas is stable with time, therefore little climate change. The validity of this assumption and other limitations of target-control regression have been described by Dennis (1980) and others.

The “gold standard” of statistical techniques for evaluation of seeding effects is the randomized experiment, and is encouraged by the weather modification operational and research communities (Garstang et al. 2004). This approach requires a careful a priori design, unlike many regression analyses that have been done post hoc. This design would be for an exploratory or confirmatory experiment that is based on findings from a preceding model or

exploratory experiment. Experimental units of a fixed duration are either seeded or unseeded (placebo) and variables (usually precipitation) from the two periods are compared. It is essential that natural precipitation in one or more nearby control areas be measured, to guard against statistical errors and to allow completion of the experiment in a reasonable period (Super and Heimbach 2005a; Super and Heimbach 2005b). Randomized experiments require numerous, precise measurement of EU response variables and typically five or more years of data to achieve statistically significant results. Since a portion of the EUs in randomized experiments must be unseeded, they are more costly and are therefore usually attempted only within research projects. There have been relatively few such experiments in the Western United States. Moreover, these experiments have not always adequately studied relevant physical processes and T&D, leading some to question their conclusions. The recent Utah WDMP randomized experiment used high-resolution crosswind control and target area snow gauges, short duration EUs, and three different statistical tests. These capabilities led to strongly suggestive positive seeding effects over just one winter (Vardiman et al. 1971; Hunter et al. 2005). While this experiment was exploratory rather than confirmatory and covered a limited area because of resource constraints, it may be used as a model for future statistical designs.

## **2.4. Benefits and Costs Versus Other Water Augmentation Technologies**

The costs of weather modification programs are often expressed per acre foot (ac-ft) of water they produce. These estimates depend on the value of water, which of course varies with local markets and the use to which the water is put. Also, the cost of operational weather modification programs varies with generator configuration, seeding agents, etc. Because demand for water in the West is increasing, so is its value. Agricultural water in California is valued from \$40 to \$50 per ac-ft (\$175 per ac-ft during drought), while the average value for hydroelectric use (by PG&E) is \$100 per ac-ft (Byron Marler, PG&E, personal communication). Municipal and industrial values are generally higher, from \$300–\$600 per ac-ft (MWD 2005).

The Wyoming pilot project conservatively estimates a weather modification cost between \$3.96 and \$7.91 per ac-ft with associated benefit-to-cost ratios of 2.4 to one ([Weather Modification Incorporated 2005](#)). Benefit-to-cost ratios of 3:1 to 10:1 were estimated for 10% mountain snowfall increases in the Sevier River basin in Utah (Super and Reynolds 1991). The authors are unaware of any calculations of benefits to ski areas, but they are believed to be high, since several ski areas have invested in the technology. The Utah Division of Water Resources has stated that the estimated direct cost of water from an 8% to 12% increase in snowpack from cloud seeding in key mountain watersheds is about \$1 per ac-ft (Utah DWR 2000). Nevada augmentation estimates have led to cost estimates of \$6 to \$12 per ac-ft. In Colorado, costs for cloud seeding generally would be less than \$20 per ac-ft, with existing programs costing about one-third that of new programs. This is because much background work has been completed and instrumentation arrays are already in place. The California DWR has estimated that an *additional* 300,000–400,000 ac-ft of new supply could be realized by seeding, with an investment of around \$7 million (DWR 2005). This represents a cost of about \$19 per ac-ft, which includes



an initial investment of an estimated \$1.5 to \$2 million in planning and environmental studies. These costs do not include randomization or evaluation components, which are recommended additions to ongoing programs. State law mandates that water from cloud seeding is treated the same as natural supply with regard to water rights.

From the foregoing, the authors conclude that the current cost of operational weather modification programs is between \$1 to \$20 *per ac-ft* of water produced, giving benefit-to-cost ratios between two to one and ten to one. Compare these figures to other, more infrastructure-intensive alternatives for increasing water supply availability. The cost of groundwater banking projects (operations) is between \$150–\$250 *per ac-ft*, plus more for building facilities (Tom Ryan, MWD, personal communication). Desalinization is presently about \$700 *per ac-ft* and there is also environmental concern with brine disposal. New dam construction costs average over \$2,000 *per acre foot*, and dams typically take 10 to 20 years to design and build (ACWA 2006). Furthermore, new dams and reservoirs are frequently opposed by environmental groups. The relatively low cost of weather modification is probably the main rationale that many water, hydropower and irrigation agencies have used to pursue it, even in the absence of rigorous scientific “proof” of its efficacy. As the demand for and the value of water grows in the West (Section 1.1), the benefit-to-cost ratios of weather modification will make it an increasingly attractive option for augmenting water supplies.

## **2.5. Proposed Tasks and Sequence**

Since it is assumed that operational cloud seeding programs will continue in California indefinitely into the future, it is proposed that the optimization of those programs be continuous as well. It is further proposed that the activities herein begin as soon as practicable, pending funding. Within the uncertainties of such funding and logistics, the following is a recommended sequence of important tasks:

1. Perform follow-on studies of the decline in operational seeding effectiveness and potential causes.
2. Development of a research roadmap. This will involve independent recommendations for critical elements of applied research and their implementation, plus input from an existing group of scientists and California seeding operators.
3. Begin field work to monitor atmospheric conditions relevant to weather modification (see Section 2.3.3, the subsection on physical evaluation techniques). Initiate data acquisition and collaboration with the HMT program.
4. Design, deploy instrumentation, and implement an applied research program that is “piggy-backed” on one or more California operational weather modification programs. The specifications of such a program would be generally described in the research roadmap, but a randomized component is essential. The steps in program implementation would do well to approximate those put forth by List (2004):
  - a. Conceptual model development (based partly on findings from items 1 and 3 above)

- b. Site selection
  - c. Exploratory field studies (extension of activities in item 3 above)
  - d. Randomized experiment (to verify seeding effects from prior statistical studies)
  - e. Evaluation
5. Analyze results from applied research program of item 4, beginning in 2008.
  6. Begin implementation of research results in operational seeding programs to optimize them, beginning 2009.

## **2.6. Recommendations**

The author offers the following general recommendations:

- Funding should be sought from various public and private sources in California (e.g., the California Energy Commission, CalFed Bay-Delta Program, and stakeholders such as hydroelectric power utilities and water supply agencies, water conservation or irrigation districts, ski areas) to support the proposed applied research.
- An education package should be developed and used to inform policy makers, stakeholders, and the public about the current state of weather modification.
- Given the availability of funding, begin the tasks outlined in the previous section.
- Synergy with other research projects related to weather modification should be sought, such as with the National Oceanic and Atmospheric Administration's (NOAA's) Hydrometeorological Testbed (HMT) program. Data from past relevant projects, such as SUPRECIP, should be analyzed for their contributions of knowledge to seeding optimization.
- A weather modification research facility should be formed in California, involving universities, research laboratories, and other interested agencies.

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## 4.0 Glossary

ACWA	Association of California Water Agencies
AMS	American Meteorological Society
CFCs	chlorofluorocarbons
DWR	California Department of Water Resources
DoI	Department of the Interior
DRI	Desert Research Institute
EUs	experimental units
FAA	Federal Aviation Administration
GPS	global positioning system
HMT	Hydrometeorological Testbed
IN	ice nuclei
LOREP	Lake Oroville Runoff Enhancement Project
LP	liquid propane
MWD	Metropolitan Water District of Southern California
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
PG&E	Pacific Gas and Electric
PIER	Public Interest Energy Research Program
SCE	Southern California Edison
SCPP	Sierra Cooperative Pilot Project
SLW	supercooled liquid water
SUPRECIP	Suppression of Precipitation Experiment
T&D	transport and diffusion
WM	weather modification
WMA	Weather Modification Association
WDMP	Weather Damage Modification Program





## **Appendix A**

### **Prioritized Cloud Seeding Research Needs for California**



## Appendix A

### Prioritized Cloud Seeding Research Needs for California

Research needs were recently identified by a team of California cloud seeding operators, including electric utility and water agency representatives (the “California cloud seeding optimization group” – see participants below). Additional input to the research needs was obtained from leading scientists in the field of cloud seeding. The California Energy Commission’s PIER representatives sponsored three meetings of stakeholders and helped organize the information. The list of research priorities developed by this group follows:

#### CONFIRM Silverman Preliminary Findings

1. Studies of existing data
  - More control streams (coastal?)
    - Better controls on basin to basin basis
    - More information about past and present operations and target areas
    - Reanalysis with better/different data

#### OPTIMIZE Seeding Programs

1. Air and surface strategies/ liability
2. Transport and Dispersion Field studies
3. Evaluations using tracers
4. Sufficient data to operate and evaluate, and better equipment and systems to achieve high reliability

Improve Conceptual models

Use new radar technologies

Ground based seeding plume lofting

Generator improvements- generator network density

Modeling (Transport and Dispersion)

Snow Data Assimilation System ([SNODAS](#))

Better ice nucleation chemistry and other agents (liquid propane)

High resolution atmospheric and cloud microphysics models

Identify liabilities and establish business based values

**The following participants of the California cloud seeding optimization group helped develop the cloud seeding research priority list:**

<b><u>Person</u></b>	<b><u>Agency</u></b>
Rob Farber	SCE
Brian McGurty	SCE
Byron L Marler	PG&E
Ed McCarthy	PG&E
Dennis Gibbs	Santa Barbara County Water Agency
Paul Scantlin	LA Dept of Water and Power
Norm Worthington	Northern California Power Agency
Pierre Stevens	Sacramento Municipal Utilities District
Tom Ryan	Metropolitan Water District of Southern California
Tom Weddle	Kaweah Delta Water Conservation District
Lynn Garver	Kings River Conservation District
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