ASSESSING ENVIRONMENTAL CONSEQUENCES OF WEATHER MODIFICATION FOR SNOWPACK ENHANCEMENT

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ABSTRACT

Weather modification for snowpack augmentation may affect wildlife dynamics, geomorphological and hydrological processes, and botanical populations, as well as increase snow loads on structures, costs of roadway snow removal, and acid deposition. Environmental consequences have been difficult to assess due to problems in verifying increases in on-the-ground precipitation. Research strategies used to assess potential environmental effects of weather modification were reviewed. Process-oriented studies and both physical and computer simulations offer the greatest likelihood for accurate assessments.

INTRODUCTION

Numerous land management practices influence the duration of seasonal snow cover and other snowpack properties. Alterations of the snowscape resulting from timber harvests, forest fires, and weather modification are examples. In the western United States, weather modification aimed at improving water supply through snowpack augmentation has been practiced since the 1950's. Humid mountainous regions in otherwise desert or semi-arid environments are prime prospects for orographic cloud seeding. Potential weather modification effects on the snowpack include changes in areal cover, accumulation rates, and duration.

Since the mid-1960's, concern has arisen over the environmental consequences of snowpack augmentation. Changes in snowpack dynamics influence diverse components of the environment, virtually all aspects of natural mountain ecosystems, and may include impacts on roadway snow removal activities and changes in snow loads on structures. Not only are the impacts diverse, but because our understanding of both the cloud physics

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and the ecosystems is often superficial, determining how cloud seeding affects the targeted ecosystems is not straightforward.

This paper briefly reviews the principles of cloud seeding for snowpack enhancement, evaluates the research strategies that have been used or proposed for environmental assessments, and recommends approaches most likely to produce viable results in the future.

PRINCIPLES OF WEATHER MODIFICATION

While cloud seeding studies have included research on fog abatement and cumulus cloud modification, not to mention several other more experimental objectives, weather modification techniques most clearly associated with regions of seasonal snow accumulation involve winter cloud seeding in mountainous areas.

In 1978, the Weather Modification Advisory Board (1978) advised the Secretary of Commerce "that seeding winter orographic storms to increase the amount of snow in the high mountainous watersheds of the West is the most advanced--and closest to significant, broad-scale operational use--of all cloud-seeding possibilities." The board added that a successful confirmatory experiment, including assessment of the seeding results, must be completed before large-scale seeding of winter storms could be considered an acceptable tool for water resource managers. Although mountainous zones in the west and on the east coast are amenable to seeding (Figure 1), the board recommended the Colorado Rocky Mountains as the site for "a sharply focused confirmatory program."

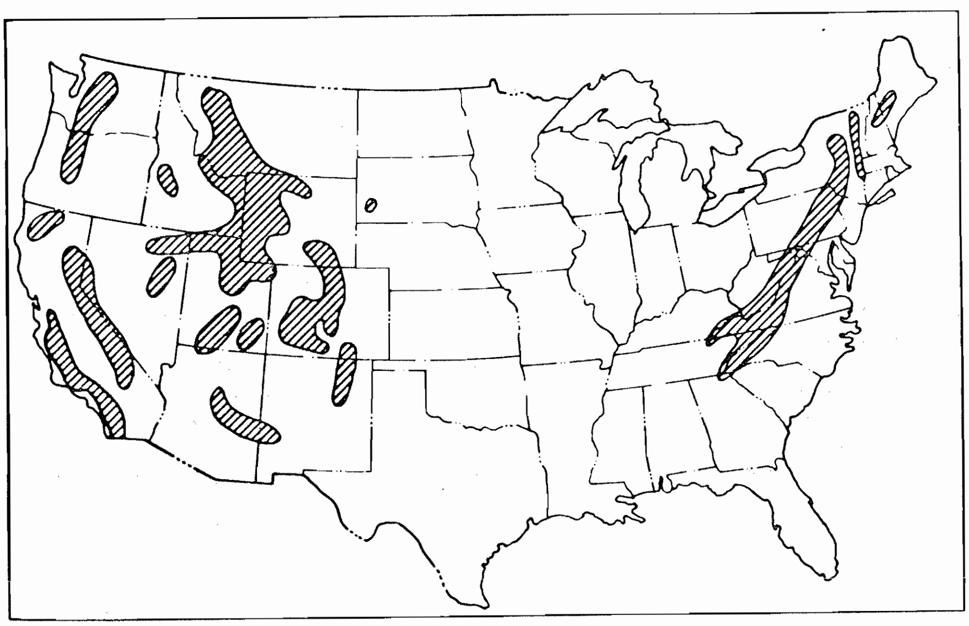

Figure 1. Regions where precipitation management may be applied to enhance snowfall from winter orographic weather systems, thus augmenting spring and summer runoff from mountain snowpacks. (Source: USDI Bur. Reclam., 1977a)

The theory of winter orographic seeding is based upon several fundamental meteorologic concepts:

1. Moist air flowing up and over mountain barriers produces water condensate at rates determined by atmospheric temperature and humidity and the rate of upward air motion. The condensate, consisting of very small droplets, tends to evaporate rapidly in the lee of the barriers due to warming associated with downward air motion.

2. The condensate may remain in the liquid state at temperatures colder than 0°C due to the relative scarcity of ice nuclei in the free atmosphere. This is particularly the case at air temperatures between about 0° and -20°C. In this condition the condensate is referred to as a "supercooled cloud."

3. Ice particles present in a supercooled orographic cloud grow at the expense of the supercooled droplets, rapidly becoming much larger than the droplets and thus achieving far greater settling velocities. Initial ice particle growth is by diffusion due to the difference in equilibrium vapor pressure over water and ice. Further growth may occur by diffusion or other processes. If total ice particle growth and the associated particle settling rate are sufficient, some particles reach the mountain barrier surface as snow particles before they evaporate or sublime.

4. The ice particle concentration is sometimes less than required for maximum precipitation fallout. In such cases, increasing the concentration through artificial means can convert more of the condensate to snow and reduce the amount of water evaporated or sublimed.

5. The artificial means of increasing ice particle concentration usually involve either cooling the region of active ice nucleation--typically by applying dry ice pellets--or by inserting artificial nucleating agents--traditionally silver iodide--in situations where natural "seed" is scarce.

The proof of the utility of winter cloud seeding to provide more useable water requires understanding and measurement of the hydrologic cycle through three states: the atmosphere, the snowpack, and finally, the stream. Although improved methods of correlating snowpack and streamflow are now available, numerous unknowns remain in the understanding of the atmospheric precipitation process. Evidence of a seeding effect should be observable in the atmosphere as well as on the ground. To date there has been minimal success in on-the-ground verification of augmented snowfall.

ENVIRONMENTAL ASSESSMENTS OF WEATHER MODIFICATION

During the 1960's concern and speculation arose over potential environmental impacts of weather modification (Livingstone, 1966; Waggoner, 1966). By 1969 when the National Environmental Policy Act was passed, Cooper and Jolly (1969) had written a major review of the ecological effects of weather modification. This and similar works (Weisbecker, 1974; Cooper et al., 1974) set the stage for a series of large-scale multidisciplinary projects in the field and laboratory--San Juan Ecology Project (Steinhoff and Ives, 1976), Uinta Ecology Project (Harper, 1981), Sierra Ecology Project (Smith, 1978), Medicine Bow Ecology Project (Univ. Wyoming, 1975)--and the Bureau of Reclamation's "Final Environmental Statement for Project Skywater, A Program of Research in Precipitation Management" (USDI Bur. Reclam., 1977b).

It has been impossible to study the actual effects of the treatment (the increased precipitation) because of the difficulty in verifying increases in on-the-ground precipitation. Therefore, most researchers have postulated environmental responses over ranges of annual augmentation increases, snow cover duration extensions, and seeding material loads. A complicating factor can be the wide range of annual variability of precipitation processes, which in the Sierra Nevada and Colorado Rockies, for instance, is at least as great as the anticipated augmentation effect (Smith and Berg, 1982; Steinhoff and Ives, 1976).

ASSESSMENT METHODS AND PROBLEMS

Various research strategies have been used to evaluate the potential environmental effects of snow augmentation programs. Usually these assessments are divided into an initial phase with a review of known information and identification of the problem, and a second phase of research to answer and explore questions and public concerns raised in the initial phase. Certain research strategies are applicable to the review phase and others to the research phase, although there is overlap. Literature citations that follow are not meant to comprise an inventory; rather they exemplify the methods and approaches discussed.

Review Phase

Three strategies have been used successfully in the review phase: workshop consensus, matrix evaluation, and literature surveys. Frequently, all three are used.

Workshop consensus involves bringing together recognized experts in fields that relate to the potential effects of snow augmentation programs to discuss and identify areas of concern and potential research problems. Examples of this method are the workshops organized as part of the Sierra Ecology Project (USDI Bur. Reclam., 1978; Smith, 1980). Their goal was to evaluate possible effects of weather modification on aquatic, botanic, and faunal components of ecosystems in the Sierra Nevada on the basis of current knowledge. The result was the identification of potential problems to be studied in the research phase of the project. The expense of holding the workshop can be a problem. Another problem is that if the same scientists will work on the research phase, their problem evaluation may have built-in biases towards research topics within their specialties (Caine et al., 1976).

A second method used in the review phase, as well as in the research phase, is matrix evaluation (Leopold et al., 1971). A sensitivity matrix uses group expertise to rank or rate environmental areas where weather modification would have significant impacts (Figure 2). This approach is useful for small projects but may be difficult to apply to large multidisciplinary projects (Cooper et al., 1974). A matrix evaluation was used in the review phase of the San Juan Ecology Project (Caine et al., 1976) and in the Skywater IX Conference on Precipitation Management and the Environment (USDI Bur. Reclam., 1977a).

The third method used in the review phase is extensive literature review, for example, Harper et al. (1978) and Smith and Berg (1980).

All three review methods, alone or in combination, usually result in statements of known information and proposed research needs that identify species or processes that respond to varying snowpack conditions. Included often are indicator species or environments that concentrate the augmented precipitation. Thus meadows or snowdrift-affected ecosystems with increased "effective" precipitation and species existing on the margins of their tolerance to moisture and snow cover duration become subjects of research interest.

Research Phase

Four approaches have been used in the research phase of snow augmentation programs: experimental study, examination of existing processes, computer simulation, and environmental monitoring.

Experimental Study

Experimental studies involve classic experimental designs (Caine et al., 1976), which can be divided into before-and-after studies and paired plots. All of these designs involve comparisons of treatment areas or samples with control areas or samples.

In before-and-after studies this is done on a temporal scale. Many of the laboratory and field investigations of silver iodide's effects on microbiology and aquatic biology fall into this category (Klein, 1978). Another example is evaluating forest tree production in relation to snowpack variations (Krebs and Tarleton, 1976; Landis and Mogren, 1976). These before-and-after studies used the record of past tree growth contained in annual rings. The before-and-after approach has seen limited use, because seeding and ecological studies often were begun simultaneously; a "before" phase does not exist.

Paired plot studies simultaneously compare control areas with treatment areas. This can be done on a large scale comparing control and treatment drainages or on a much smaller scale comparing localized control and treatment plots. No examples of large-scale plot studies were found probably due to problems associated with this

ENVIRONMENTAL ISSUE / Environmental Setting	Erosion		Avalanches	Microclimate		Water Yield	Water Quality		Fluvial Geomorphology	
	Surface Erosion 1.33	Mass Wasting 1.67	2	Snow Duration 2	Soil Moisture 1	1.75	Physical 1.33	Chemical 1.33	Channel Proc 1.4	Sediment Yield 1.4
Alpine	1 (1)	2 (2)	2 (1)	2 (2)	1 (2)	2 (2)	1 (2)		1 (1)	2 (1)
Forest		1 (2)	2 (1)	2 (2)	1 (2)	2 (3)		1 (1)	1 (2)	
Rangeland	1 (2)	2 (2)			1 (2)	1 (1)	1 (2)	1 (1)	1 (2)	1 (2)
Agricultural	2 (3)				1 (2)	2 (3)	2 (3)	2 (2)	2 (2)	2 (2)
Unstable Stream Channels									2 (1)	2 (2)

1 — detectable but insignificant
2 — readily detectable, sometimes important

(1) — mostly empirical
(2) — partly deterministic
(3) — well-developed

Figure 2. Sensitivity matrix for abiotic issues. (Source: USDI Bur. Reclam., 1977a)

approach. These problems are listed below. Examples of localized paired plot studies are numerous. Many involve the use of snow fences to vary snow deposition depths within grass or herbaceous community types (Weaver and Collins, 1977; Webber et al., 1976; Bock, 1976). Others extend the snow cover duration by manually augmenting snow on randomly selected vegetation plots (Knight et al., 1975; Knight and Kyte, 1975).

Several types of problems are associated with experimental studies. One problem involves the scale of treatment and control areas. Snow augmentation programs usually have major drainages or entire mountain ranges as their target areas. At such large scales it is difficult or impossible to find comparable control and treatment areas. There is also the problem of "overlap" effects from the target areas onto surrounding areas; the control area may not be totally unaffected by the treatments.

A second type of problem involves temporal considerations. How many years must the experiment be continued before effects become noticeable and distinguishable from the intrinsic natural variability of the floral and faunal populations? What kind of effects do previous years have on the current vegetation processes being examined? Are there effects that will only become evident after long term treatment, e.g., after 50 years of cloud seeding (Cooper et al., 1974)? Morel-Seytoux and Saheli (1973) suggested that record periods on the order of decades will be required to verify annual hydrologic responses to snowpack augmentation. Identification of annual ecological changes probably requires time spans at least as long.

A third type of problem is the possible lack of similarity between the treatment effects and the real effects of cloud seeding. Webber et al. (1976) identified several differences between snow-fence treatments and cloud-seeding effects in alpine areas: (1) snow fences are ineffective on natural snow accumulation sites because they are rapidly covered by snow. These natural sites are probably where any additional snow created by augmentation programs will be deposited. (2) The fences must be set up in areas with sufficient wind velocity to deposit snow. These areas are naturally low accumulation sites due to the wind and will probably show minimal snow increases as a result of snow augmentation programs. (3) Snow fences must be disassembled during the summer due to their effect on the plant microenvironment.

Study of Existing Processes

In "process" studies existing variations in processes relating to ecosystem-snow interactions are examined through space or time or both. There are numerous examples (spatial variation--Weaver, 1974; Webber et al., 1976; Harper, 1981; temporal variations--Sweeney and Steinhoff, 1976; Blaue and Fechner, 1976; Evans and Patrick Reid, 1976; Knight et al., 1975). Caine (1976) assessed rock weathering, soil movement, rockfall, mudflow and other components of the Colorado alpine erosion/sediment transport regime by studying existing processes. The objective is not to identify environmental effects but rather to assess median and extreme responses of the ecosystem to natural variations in snow depth and duration. The proposed augmentation effect is then assumed to fall within the range of the observed ecosystem responses. In practice, if background information is minimal or nonexistent, the field observation period must span at least 3 years and more typically 5 to 7 years.

The process-study approach has many advantages and few problems. Some of the advantages are:

- it adds to the basic scientific knowledge of the study area,
- it does not require knowledge of the exact effects of cloud seeding on the snowpack in order to conduct research; this knowledge is only needed in the final evaluation stage,
- it allows use of existing knowledge,
- it gives results that can be expanded in the future as understanding of the systems improves,
- it requires no ecosystem manipulations and thus reduces costs,
- under appropriate circumstances, it produces results that are applicable to other areas (Caine et al., 1976).

Some of the problems of process study are:

- the selection of representative and comparable study sites,
- statistical considerations relating to appropriate tests and confidence levels,
- the need for uniformity of methods if the research is conducted by more than one scientist, and
- the inability to detect actual environmental changes given the relatively short observation period (Caine et al., 1976; Harper, 1981).

Because most of these problems are encountered in ecological research and their solutions can be drawn from other scientific sources, they present no real problems to the study of variations in existing processes.

Computer Simulation

Although computer simulation has been highly recommended (Cooper et al., 1974; Caine et al., 1976), examples of its use in the study of biological impacts of snow augmentation are rare. One example is the work of Webber et al. (1976), who used previously developed models that had already been extensively modified and refined for application in the International Biological Programme United States Tundra Biome Project. Two other examples are the works of Israelsen et al. (1975), who adapted hydrologic and aquatic ecosystem models to predict changes in biomass standing crops of egg, juvenile, and adult stages of several major fish species; and Parker and Condit (1975), who estimated change in daily phytoplankton standing crop for a Wyoming lake.

The relative rarity of the use of computer simulation models in studying biological impacts of snow augmentation results from the problems associated with computer simulation:

- the data needed to develop and apply simulation models to biological systems in target areas often are not available,
- developing and testing an accurate simulation model requires data on many parts of the biological system; gaps weaken the validity of the model,
- the realization that biological simulation models in relation to snowpack augmentation involve many complex interactions and thus will never be as precise as hydrological simulation models, and
- the amount of time, computer and biological expertise, and money that must go into the development of such models is large.

Although more tractable than biological models, hydrologic modeling of snow augmentation effects is also uncommon. Leaf (1975) simulated evapotranspiration, soil recharge, snow cover duration and water yield changes that resulted from postulated snowpack augmentation levels for a Colorado watershed.

Simpler models (regression, bivariate analysis, gradient models, etc.) are extensively used to study existing variations in biological processes (Webber et al., 1976; Krebs and Tarleton, 1976; Ostler et al., 1982) and to estimate extensions of snow cover duration (Smith and Berg, 1982) and changes in stream channel geometry and sediment yield (Rango, 1970).

Ecosystem Monitoring

Most data collected using the three previous research methodologies could be used for monitoring purposes, although no examples were found of ongoing monitoring projects. Several studies have had as stated objectives the development of pre-cloud-seeding inventorial data bases. Included are the Medicine Bow Ecology Project analyses of big game-snow dynamics (Ward et al., 1975; Strickland and Diem, 1975). Before a long-term monitoring project is established, its goals should be explicitly stated. These will influence what is to be monitored and how. The Weather Modification Advisory Board (1978) estimated that detection of distinct environmental effects would be possible only after 20 years of continuous cloud seeding.

Problems associated with monitoring projects are the large amount of money needed to sustain a long-term project, the need for continuity of methods and personnel, and difficulty in separating natural variation in the snowpack from variations imposed by cloud seeding. Many of the considerations and problems associated with experimental studies also apply to monitoring studies.

Long-term ecosystem responses are a major unresolved assessment problem. Upon completion of the draft Project Skywater Programmatic Environmental Statement by the Bureau of Reclamation, Howell (1977) provided a perspective regarding environmental questions on cloud seeding for precipitation augmentation:

> Studies of physical and biological processes relating precipitation and ecosystem changes show relatively few discernible effects, all of them minor in nature and magnitude. Direct effects of nucleating agents no longer appear consequential. Since no acute problems have surfaced, the focus is likely to shift to possible long-term effects on ecosystems as a whole, where changes associated with natural precipitation gradients and climatic fluctuations provide a model for those to be expected from precipitation management. The weakness of environmental impacts of weather modification compared to the consequences of other human actions renders it unlikely that these impacts will be decisive within a behavioral framework.

RECOMMENDATIONS

Several recommendations stem from our consideration of the research methodologies used in recent assessments of the potential effects of snowpack augmentation:

(1) develop process-oriented studies;

(2) consider computer simulation when appropriate models, data, and expertise are available. Recently developed forest succession models should be applicable to evaluations of the long-term potential for ecological change (Shugart et al., 1980). Simulation techniques are suited also to analyzing of cumulative effects of weather modification and timber harvest, pesticide application, grazing or other management actions;

(3) perform physical simulations (e.g., snow fences), which can provide interesting information that may be applied cautiously to impact analysis;

(4) use experimental approaches in studying effects on long-term tree growth when appropriate weather data are available.

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