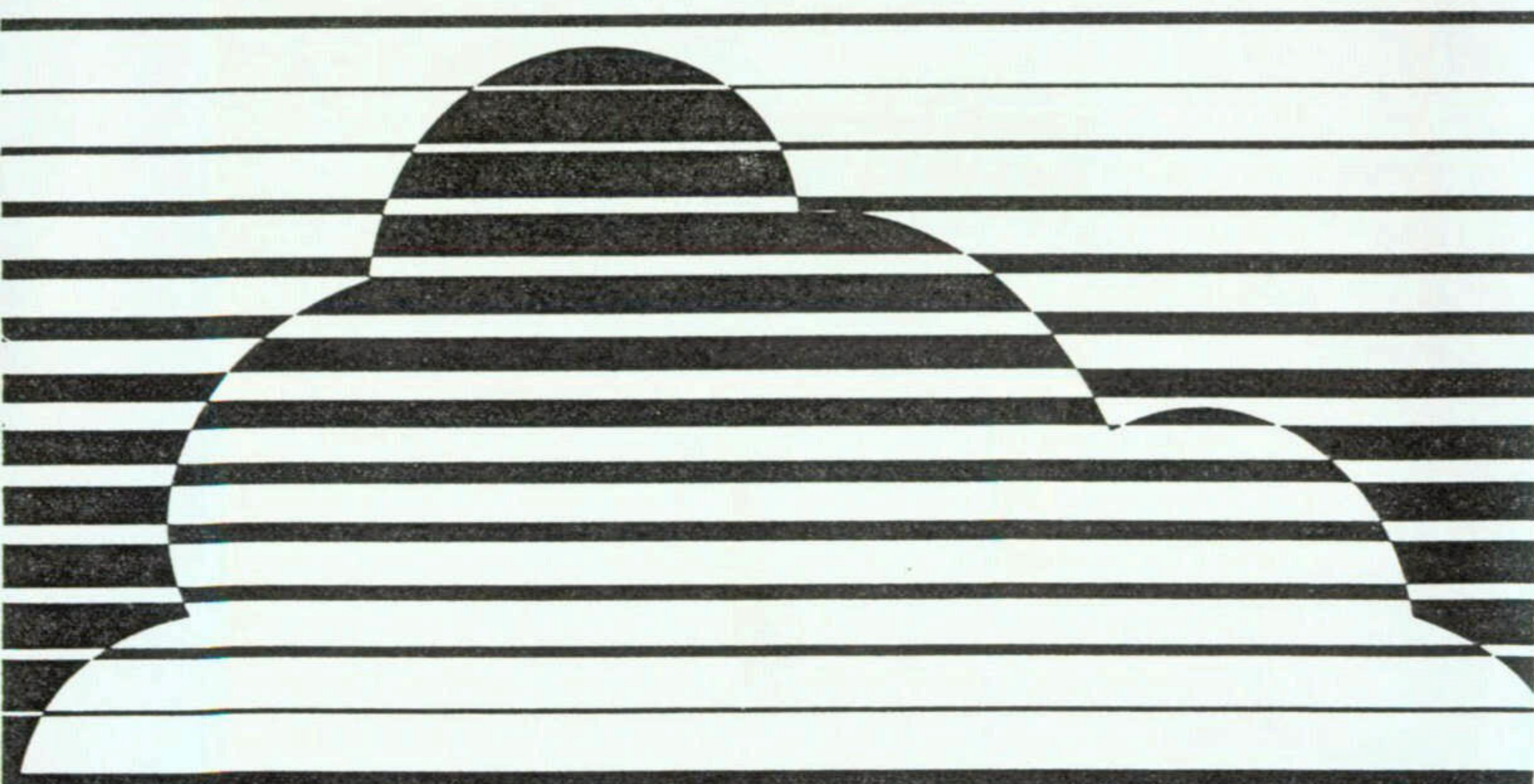
A SIMULATION OF THE COSTS OF REMOVING SNOW FROM COUNTY HIGHWAYS IN COLORADO

MARCH 1983



A Simulation of the Costs of Removing Snow from County Highways in Colorado

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Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

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Purpose

The purpose of this study is to assess procedures and estimate costs of removing snow from county highways in the mountains and on the Western Slope of Colorado. The study, conducted by the Weather Modification Program of the Colorado Department of Natural Resources, was undertaken because commissioners and citizens of some Colorado counties have expressed concern that weather modification increases costs of removing snow.

Procedure

Selection of Counties.

Eight mountain and Western Slope counties were selected for study. Eagle, Lake and Routt in northern and central Colorado and La Plata, Ouray and San Juan in southwest Colorado were chosen because their residents have expressed interest in or concern about weather modification. Garfield and Rio Blanco, on the Western Slope, were chosen because they are in the area where a cloud seeding project to increase the flow of the Colorado River has been proposed by the Bureau of Reclamation.

Assessment of Available Data.

Quantifying county expenditures for snow removal requires detailed information about labor, such as the number of hours each employee spends removing snow and performing related duties; capital expenditures including the purchase price, depreciation and maintenance costs of equipment; and the cost of materials like cinder and chains. Since most counties do not keep detailed records of these expenses, we estimate them with a computer simulation model.

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The Simulation Model.

The simulation model estimates snow removal costs using information about wages, machines and removal procedures gathered by interviewing road maintenance foremen in each county and daily snow amounts recorded at National Weather Service cooperative observer sites. Snowfall records from past winters were used so costs could be estimated for winters of low, average and high snowfall. The model also estimates costs of mop-up (pushing back banks, clearing drifts and sanding slick spots on days following storms) and overtime.

Labor costs are computed only for the time employees spend removing snow. Labor of mechanics is included in the "rental rate" applied to each machine. The labor of office staff is excluded because it is difficult to tie their duties to daily snowfall. Costs of supplies are excluded, because they are difficult to determine and because initial estimates indicate that they are insignificant compared to costs of labor and machines. Costs of operating, maintaining and repairing equipment were estimated by using hourly "rental rates" calculated by the Colorado Department of Highways.

Foremen reported that the effort required to remove given amounts of snow depends on characteristics of storms such as wind, density of snow, time of day and duration. We developed methods to account for time of day and duration; wind and density of snow were accounted for by asking foremen to "abstract away" the extreme and consider typical conditions.

Simulated Augmentation of Snow Amounts.

The simulation model can estimate snow removal costs when recorded snowfall amounts are increased to simulate effects of seeding. In this study, snow amounts in a random sample of one-third of the storms in the winters examined are increased 25 percent. Twenty-five percent was chosen because Colorado State University scientists have indicated that these increases in snowfall are possible if storms are seeded carefully and knowledgeably. Snow amounts were augmented in only one-third of the storms because meteorological conditions favorable to seeding are thought to exist in about one-third of the winter storms in the Colorado mountains. This augmentation scheme resulted in increases in seasonal snowfall which ranged from 4.5 to 9.7 percent.

General Information

Foremen in different counties reported different amounts of time to clear given amounts of snow. Removal strategies also vary: in some counties all equipment operators are sent out initially, but in others, only some are sent out unless snowfall is heavy.

Foremen reported that the effort required to remove snow increases rapidly when snowfall exceeds one or two inches. Removing four to six inches of snow requires all operators to work a full day. Removing nine or ten inches requires little more effort than removing six inches, however, since the operating speed of the equipment remains fairly constant. Amounts greater than ten inches were reported to require overtime in most counties studied.

Results

Costs of Removing Snow from Natural Storms.

Estimated costs per employee of removing snow from natural storms range from about $1,300 in Eagle County in a winter of average snowfall to more than $11,000 in San Juan County in a winter of high snowfall. Estimates for each county generally are highest in winters of high snowfall and lowest in winters of low snowfall. Exceptions occurred in Eagle, Lake and Ouray counties where some of the winters examined had many small storms; small amounts of snow require more effort per inch to remove than large amounts.

Costs of Removing Augmented Snow.

Estimated costs of removing snow increase when recorded snow amounts are augmented. Increases in total costs of removal range from 0.8 percent in Garfield County in a low-snowfall winter to 12.6 percent in Lake County in a high-snowfall winter. The average cost increase, over all counties studied, is 6.1 percent in winters of high and average snowfall, and 4.9 percent in winters of low snowfall.

Recommendations for Record-Keeping

Actual effects of cloud seeding on the costs of removing snow cannot be determined definitively until more accurate records of employee and equipment expenses are available. Recommendations for daily record-keeping include:

1. Number of hours each employee spends performing typical tasks (e.g., plowing snow, repairing highways, maintaining machines); and

2. Number of hours each machine is used for various tasks (e.g., clearing of snow, hauling cinder), maintenance costs, fuel consumption.

Forms could be designed and procedures developed to make this information easy to collect.

PURPOSE

The purpose of this study is to assess procedures and estimate costs of removing snow from county highways in the mountains and on the Western Slope of Colorado. The study, conducted by the Weather Modification Program of the Colorado Department of Natural Resources, was undertaken because commissioners and citizens of some counties have expressed concern that weather modification increases costs of snow removal.

THE PROBLEM IN PERSPECTIVE

Colorado's expanding population and industry have placed increasing demands on the state's supplies of water. Problems caused by water shortages are most acute during periods of low snowfall in the mountains because runoff from melting mountain snowpack typically provides approximately 70 percent of the state's water. For example, when snowfall in most mountain areas was far below normal in 1976-77 and 1980-81, several sectors of the state's economy--particularly the ski industry--were affected severely.

In the spring of 1977 and the following winter, local water-user agencies and the state of Colorado sponsored weather modification (cloud seeding) in the Colorado mountains for drought relief. Each winter since then, ski areas, water-users, and local governments and businesses have funded seeding programs to augment mountain snowpack.

Seeding has been proposed by the Bureau of Reclamation as the most promising means of augmenting the flow of the Colorado River (CREST Briefing Document, 1982). Additional water is needed in the Colorado River Basin to meet local demands (population and industrial expansion, recreation, and hydroelectric power generation) and to fulfill a national obligation to provide Mexico with 1.5 million acre-feet of water annually. The Westwide Study Report (1975), which analyzes critical water problems facing 11 western states and compares weather modification to other augmentation measures like importing water, desalting seawater or geothermal brines, and managing vegetation, concludes that "weather modification appears to be the most promising source of new water supply in the Western United States."

Cloud seeding is controversial. First, some scientists are not convinced that it works (Morel-Seytoux, 1977; Katz and Glantz, 1979). Others are convinced, after two decades of experimentation, that it can work--if it is conducted carefully and knowledgeably (Elliott et al., 1978; Mielke et al., 1981). The Weather Modification Advisory Board (1978:35), charged with assessing weather modification, concluded that "there is strong evidence that snowfall from winter storms over Colorado mountains can be increased by 10-20% provided that seeding can be limited to clouds having certain well-defined characteristics."

Second, the benefits of winter seeding are not distributed uniformly. The people who may suffer adverse effects are, in general, not the ones who enjoy the benefits (Sonka, 1979:31). In Colorado, the disparity is probably most evident in small mountain communities whose residents experience the inconvenience of additional snowfall but reap few of the benefits enjoyed downstream by municipal water-users and irrigation interests. The potentially adverse socio-economic impacts of seeding on mountain areas include costs of early-season supplemental feeding of cattle, more avalanches, and inconvenience and threats to the health of the elderly (Rudel, Stockwell and Walsh, 1973; Weisbecker, 1974; Farhar and Rinkle, 1976). Another impact often mentioned is the cost of removing snow from highways.

Colorado citizens and representatives of county governments often claim at permit application hearings that cloud seeding increases the cost of snow removal. In 1981, commissioners in one county passed a resolution declaring opposition to cloud seeding until counties receive restitution for the tax money they spend dealing with its consequences. Earlier, Farhar and Rinkle (1976:51) had reported that county governments in California were concerned about the possible costs of removing snow that a program to augment snowpack in the Sierra Nevada might produce.

The Weather Modification Advisory Board (1978:130) urges that the problems caused by disparate benefits not impede the use of weather modification but instead stimulate the identification of adverse impacts and the development of policies to mitigate them. The Colorado Department of Natural Resources Weather Modification Program, in cooperation with the Bureau of Reclamation, is conducting research in this area. This study is part of that effort.

PRIOR STUDY

Over the years, several authors have stressed the need for research into the social consequences of weather modification--yet few definitive studies have been conducted. In 1966 the National Science Foundation's Special Commission on Weather Modification concluded that, "The need is great to assess more fully the social implications of weather and climate modification." Twelve years later the Weather Modification Advisory Board (1978:123) stated that, "Study of the societal aspects of weather modification has been grossly underfinanced and essentially unattended."

The investigation of snow removal has been mainly speculative. Hurley (1968) points out that hidden costs such as snow removal may increase the overall costs of seeding to augment the Colorado River. Weisbecker (1974:232) notes that increased snowfall from seeding may cause local governments to spend more money for snow removal.

Cooper et al. (1974:59) claim that snow augmentation would increase removal costs in the Sierra Nevada. They indicate that the amount of the increase, however, would depend on the nature of augmentation. "The adverse effects . . . would be greatly reduced if *seeding resulted in increased intensity of snowfall instead of duration*" (1974:60). By way of example, they point out that plowing 11 inches of snow instead of 10 inches would make much less difference than operating plows for 11 hours instead of 10.

Unfortunately, scientists do not know yet if seeding causes storms of greater intensity, or greater duration, or both. Colorado State University researchers have interpreted findings by Chappell et al. (1971) to suggest that the main effect of seeding is to extend the period of precipitation (Mielke et al., 1981:647), but investigation of this important question continues. An answer to it must be found before added costs of snow removal can be determined definitively.

Harris (1981:98), in his assessment of environmental impacts of the Sierra Cooperative Pilot Project, states that increased snowpack could affect snow removal in communities located more than 6000 feet above sea level. He does not discuss the extent of this effect but indicates that it would depend on the efficiency and adequacy of snow removal operations.

The California Department of Transportation reports that "recorded data do not provide us with the refinement necessary to analyze costs involved in snow removal for a small incremental increase in precipitation" (Harris, 1981:99). The Department indicates, however, that small increases in snowfall would result in little additional cost, because the men and equipment used to remove the extra snow are already necessary for basic winter highway maintenance. The Department also states that wind and ice close roads more often than snow does.

PROCEDURE

Selection of Counties

Eight mountain and Western Slope counties in Colorado were selected for study. Eagle, Lake and Routt in northern and central Colorado and La Plata, Ouray and San Juan in southwest Colorado were chosen because their residents have expressed interest in or concern about weather modification. Garfield and Rio Blanco, on the Western Slope, were chosen because they are in the area where a cloud seeding project to increase the flow of the Colorado River has been proposed by the Bureau of Reclamation.

The counties chosen vary considerably in size. Garfield and Rio Blanco, the largest, contain approximately 3,000 square miles; Lake and San Juan, the smallest, contain approximately 500 square miles. Miles of highway maintained in the winter range from about 15 in San Juan County to approximately 900 in Rio Blanco County. All counties studied contain high mountains with peaks of at least 11,500 feet and, except for Lake and San Juan, also relatively low, flat areas. For example, the northern half of La Plata County is mountainous but the southern half lies in the basin south and west of the San Juan Mountains. Variation of terrain within the counties makes it difficult to group them by elevation or topography--characteristics which may be related to snow removal procedures and costs.

Although these counties were not selected randomly, we have no reason to believe that snow removal costs and procedures differ greatly in Colorado mountain and Western Slope counties not selected.

Assessment of Available Data

Quantifying county expenditures for snow removal requires detailed information about labor, such as the number of hours each employee spends removing snow and performing related duties; capital expenditures including the purchase price, depreciation and maintenance costs of equipment; and the cost of materials like cinder and chains. Since the counties studied do not keep detailed records of these expenses (except, La Plata which recently has begun to keep daily records of employee activities and machine use to document possible future requests for federal aid in winters of heavy snowfall), we estimate them with a computer simulation model. Recommendations regarding the types of records that counties could keep to determine costs more accurately appear in the Appendix.

Collection of Data for the Model

Data for the model were gathered by interviewing the foremen who direct snow removal operations in each county. The foremen were asked to describe:

1. What resources are available--including personnel and their rates of pay, equipment; and

2. How resources are typically used when it snows--including the minimum amount of snow requiring removal, the time and equipment required to remove various amounts, the time required for mop-up (pushing back banks, clearing drifts and sanding slick spots on days following storms) and policies for overtime.

Foremen reported that the time required to remove given amounts of snow depends on characteristics of storms such as wind, density of snow, time of day and duration. These characteristics are discussed below. We developed methods to account for time of day and duration. Wind and density of snow were accounted for by asking foremen to "abstract away" the extreme and consider typical conditions. Foremen were asked to identify and discuss special problems (like those caused by extreme wind) before we asked them to estimate the time required to remove given amounts of snow under typical conditions.

Foremen reported that amounts of snow from a given storm could vary considerably within their districts. This was especially true in mountainous districts where snow depth varies with elevation and the angle of the wind to nearby mountain barriers. Most foremen could, however, identify a pattern of variation: "When we get three inches here at the shop, six or eight usually fall on the ridge." Although the reported pattern did not apply to all storms, we asked them to consider it when indicating how employees and equipment are deployed.

We asked how many operators and how much time usually would be required to clear the district's roads when a certain amount of snow fell at the shop. We expect that this method, which assumes a typical pattern of variation, may result in underestimated costs, since there undoubtedly were times when it did not snow at the shop but did snow elsewhere in the district.

Foremen indicated that time of day and traffic affected snow removal: a light to moderate overnight snowfall requires less effort to remove than a similar amount that falls during the day when traffic is heavy. They reported that duration of the fall also affects removal. One foreman indicated, for example, that a steady day-long fall of one-half inch an hour requires continual clearing and greater effort than a larger amount of snow falling over a shorter period.

Wind often affects removal, according to foremen. They indicated that drifts several feet high could block roads even though actual snowfall was less than 12 inches; they also pointed out that drifting often occurs long after snow has stopped falling. Foremen claimed that, all else being equal, wet snow was more difficult to move than the "fluffy" snow common in colder months. On the other hand, wet snow is typical in warmer months when longer days and higher sun angles result in more melting and easier removal.

Computing costs of operating, maintaining and repairing equipment presented problems since most counties do not keep detailed records of these expenses. We estimated them by using hourly "rental rates" calculated each year by the Colorado Department of Highways (Colorado Department of Highways, 1982). These rates, which include fuel, maintenance and repair, depreciation and replacement allowances, are calculated for many types of machines including equipment used by the counties for snow removal. For example, hourly rates for a road grader (100 horsepower and up) are $26.47; hourly rates for a 3/4 ton pickup truck are $6.38. Machine hours required to remove given amounts of snow were easy to estimate, because they are the same as operator hours, which are estimated from information gathered from the foremen.

The Simulation Model

The simulation model estimates snow removal costs using information about wages, machines and removal procedures gathered from road maintenance foremen in each county and daily snow amounts recorded at National Weather Service cooperative observer sites. The model also estimates costs of mop-up and overtime.* Overtime, paid at time-and-a-half rates, is calculated when recorded snowfall exceeds the amount that foremen reported could be cleared during normal working hours, or when evening or early morning snow is heavy enough to require removal at times other than normal work hours.

Labor costs are computed only for the time employees spend removing snow; time spent on other tasks such as road and bridge repair is excluded. Labor of mechanics is included in the "rental rate" applied to each machine. The labor of office staff is excluded because it is difficult to tie their duties to daily amounts of snow. Costs of supplies are also excluded, because they are difficult to determine and because initial estimates indicated that they are insignificant compared to costs of labor and machines.

Snowfall Data

Daily snow amounts, recorded at the National Weather Service cooperative observer site in or nearest the town in which each county shop is located, were obtained from the state climatologist. Records from past winters at approximately the 20th, 50th and 80th percentile of long-term annual snowfall** were selected at each site so costs could be estimated for winters of low, average, and high precipitation. (Sites and winters used in each county are listed in Table 1.) Costs of removal, although estimated from snowfall records in past winters, are based on 1982 wages and machine costs.

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*The model was developed on an IBM personal computer. A listing and diskette are available at the Bureau of Reclamation, Division of Atmospheric Resources Research, Denver, Colorado.

**For example, "20th" indicates that only 20 percent of the winters of record had lower annual snowfall.

Since snowfall is recorded at most sites only once a day in the early evening, storms that begin in one time period and end in another are considered to be distinct events occurring on concurrent days. On the other hand, when two distinct storms occur in the same 24-hour recording period, they are considered to be a single event. The effects of these assumptions on removal costs are not known but assumed to be negligible.

TABLE 1
National Weather Service observation sites and winters of low, average and high snowfall in each county

County	Observation Site	Winters of Indicated Snow Amounts: Low	Average	High	Long-term Mean Annual Snowfall (inches)
Eagle	Eagle	1958-59	1964-65	1961-62	48
Garfield	Glenwood	1946-47	1957-58	1936-37	71
	Rifle	1935-36	1971-72	1972-73	41
Lake	Leadville	1965-66	1966-67	1969-70	128
La Plata	Durango	1946-47	1962-63	1964-65	70
Ouray	Ouray	1950-51	1967-68	1978-79	149
Rio Blanco	Meeker	1952-53	1954-55	1957-58	86
Routt	Hayden	1965-66	1954-55	1967-68	108
	Steamboat	1937-38	1941-42	1964-65	166
	Yampa	1971-72	1957-58	1949-50	118
San Juan	Silverton	1975-76	1949-50	1948-49	159

Start Times of Storms

Knowing the time of day when storms occur is important since traffic compounds problems of snow removal and employees sometimes work overtime when snow falls in the early evening or overnight. Observations are not taken frequently enough at most cooperative observer sites to determine time of fall. Researchers have studied time of fall at several sites in Colorado, however, (Grant, ed., 1969; Crow, 1969) and their findings, discussed below, are used to assign start times of each storm.

Figures 1-4 show variations in times of recorded snowfall at Hot Sulphur Springs in central Colorado and at Ouray, Durango and Silverton in the southwest. A marked peak in frequency during the early morning followed by a dip around noon is typical at Hot Sulphur Springs and at other stations in the north and central parts of the state (Grant, ed., 1969). The pattern at Ouray is somewhat similar. But in Durango, snow is more likely to fall in the morning and less likely to fall in the late afternoon and evening, and in Silverton snow is most likely to fall in the late afternoon. Grant, ed., (1969) attributes these differences to exposure--that is, to the location of observation stations relative to surrounding mountains.

We used the probabilities of occurrence of snow depicted in Figures 1-4 to assign a start time to each storm randomly. The Hot Sulphur Springs variation was used for counties in north and central Colorado; Ouray, Silverton and Durango variations were used for Ouray, San Juan, and La Plata counties, respectively.

We assumed that the probability of storms starting at a given hour is, in the long run, identical to the probability of snow falling during the same hour. If, for example, snow at a given station is twice as likely in the early morning as in the early afternoon, the model assigns start times that reflect this pattern.

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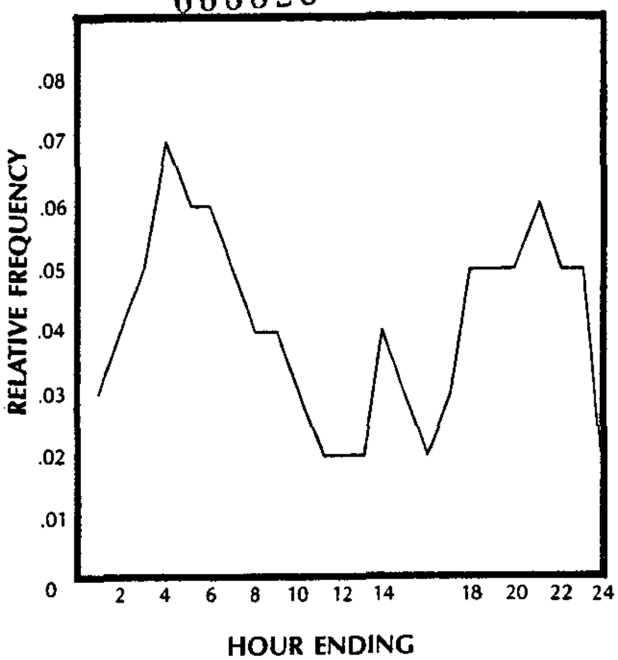

Figure 1. Diurnal frequency of snowfall at Hot Sulphur Springs, November-April, 1964-1967 (adapted from Crow, 1969).

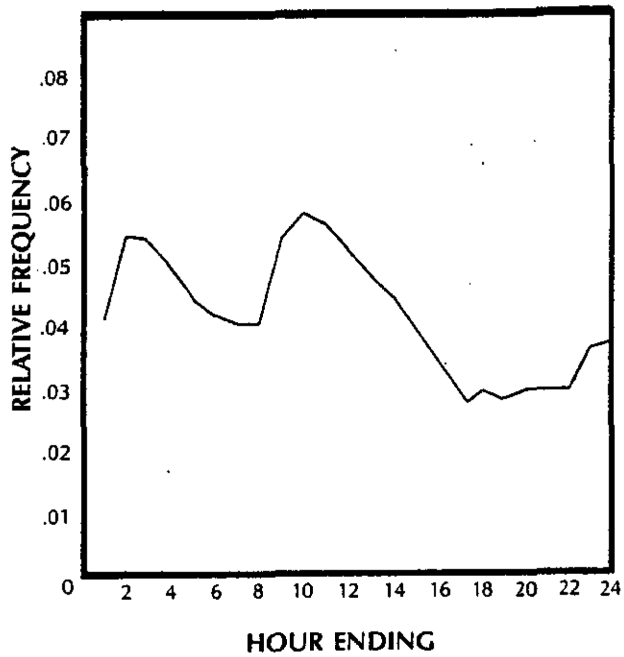

Figure 2. Diurnal frequency of snowfall at Durango, November-April, 1948-1968 (adapted from Grant *et al.*, 1969).

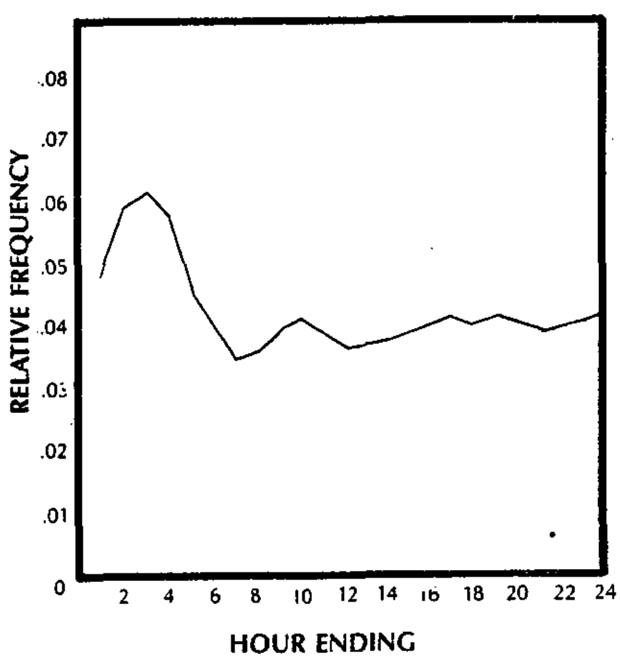

Figure 3. Diurnal frequency of snowfall at Ouray, November-April, 1948-1968 (adapted from Grant *et al.*, 1969).

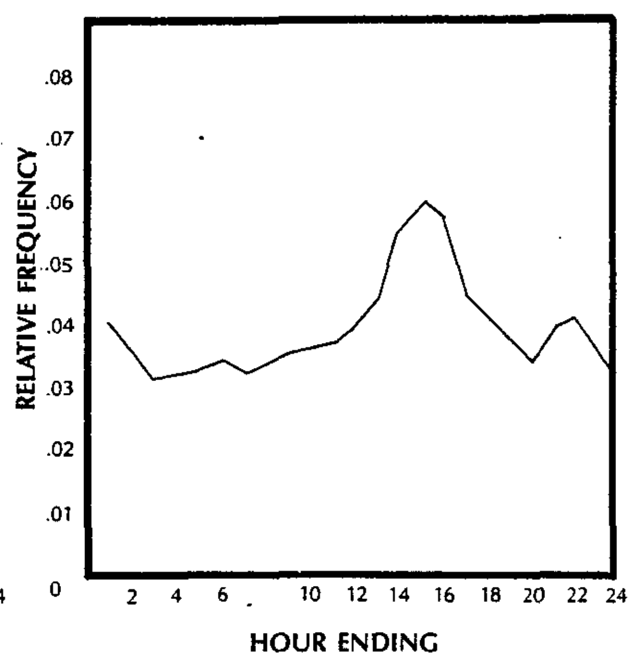

Figure 4. Diurnal frequency of snowfall at Silverton, 2NE November-April, 1948-1968 (adapted from Grant *et al.*, 1969).

Duration of Storms

Foremen indicated that the effort required to remove a given amount of snow depends on the duration of its fall. In general, the shorter the storm, the less time required for removal. Because snowfall at the observation sites used in this study is recorded only once each day, we could not determine the duration of particular storms for which the model estimates removal costs. We estimated duration by examining precipitation records at hourly recording sites in Colorado with similar elevation, exposure and average annual snowfall. Data from these sites were obtained from Professor Lewis Grant and the Colorado State University Atmospheric Science Department. Storms at these sites were defined by consecutive hours of precipitation of at least .01 inch. Total precipitation was computed for each storm and regression equations relating duration to amount of snow were used to assign a duration to each storm.*

We assumed that the duration of augmented storms that yield a given amount of snow is identical to the duration of storms that yield the same amount naturally.

*Precipitation (inches of melted snow) was converted to inches of snow assuming a density of .08 grams/cubic centimeter (about 12 inches of snow per inch of water), the mean density observed by Grant and Rhea (1973) over 12 years at a dense network of stations near Climax, Colorado.

Simulated Augmentation of Snow Amounts

The simulation model can compute snow removal costs for a variety of augmentation scenarios. For this study we augmented by 25 percent recorded snow amounts in a random sample of one-third of the storms in each winter examined. Storms were defined by snow of at least .1 inch. We chose 25 percent because it is the overall increase in precipitation identified by Mielke et al. (1981) in their reanalysis of the Climax experiments; we chose to augment one-third of the storms because the meteorological conditions for which seeding is thought to be effective were observed on 34 percent of the non-seeded experimental days during the Climax experiment (Chappell, 1970). This augmentation scheme resulted in increases in seasonal snowfall which ranged from 4.5 to 9.7 percent (see Tables 2 through 12).

The largest storms--those with snowfall greater than the 95th percentile of long-term 24-hour amounts--were not augmented. Snow produced by these storms ranged from 6.5 inches at Rifle to 10.0 inches at Silverton. These upper limits were chosen because safety precautions set forth in state-granted weather modification permits usually curtail seeding of the largest storms.*

Deciding what expenses to attribute to augmented snowfall is difficult because maintaining highways requires a complement of people and machines whether or not seeding takes place. Also, since snowfall often varies each winter by more than 10 to 20 percent--the amount of additional snow per season that some scientists estimate seeding could produce--and since seeding is less likely in winters of heavy snowfall, it is not clear that counties equipped to handle natural storms would need more people and equipment to handle augmented storms. Additional snow is, however, likely to require employees (and machines) to spend additional time on the road. We estimate the cost of removing snow produced by seeding by estimating employee and machine expenses of this additional effort.

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*For example, permits granted in 1982 for seeding in the Colorado mountains specified that seeding be curtailed when heavy precipitation that could contribute to avalanches or severe weather conditions was occurring or predicted.

GENERAL INFORMATION

Most of the counties studied are divided into road maintenance districts (not all of which, for lack of snowfall records, are included in this study). Routt has three districts and La Plata has four; Lake and San Juan, on the other hand, each have only one district. Although most equipment is housed and maintained in "county shops," in very rural counties operators sometimes keep machines at their homes. The "typical" district in the counties studied has one foreman, seven operators and one or two mechanics who work in the shop maintaining and repairing equipment.

All counties studied use "maintainers" (road graders) to remove snow. These machines usually are equipped with external wings to increase swath. Some counties also use dump trucks equipped with blades and wings and drop-in sanders. The age of the equipment varies considerably, and some counties still use machines built in the 1950s. New equipment is very expensive--a top-of-the-line maintainer costs well over $100,000.

The primary responsibility of removal crews in the counties studied is to maintain roads used by school buses and the postal service. When snow falls overnight, crews often start removing it as early as 4:00 a.m. Work continues until the roads have been cleared or until most residents have returned home in the evening. In counties frequented by tourists, crews sometimes clear roads as late as 11:00 p.m.

When snow begins to fall in the counties studied, the foremen, equipped with four-wheel drive pickup trucks, survey road conditions. Some counties sand busy intersections and steep hills as soon as snow accumulates, but snow removal usually does not begin until one or two inches have fallen. Once removal begins, foremen check for trouble spots or equipment breakdown until clearing has been completed. Snow slides complicate snow removal in very mountainous counties such as San Juan. Safety dictates that an extra person watch the clearing of slides.

Foremen in different counties reported different amounts of time to clear given amounts of snow. Removal strategies also vary: in some counties all operators are sent out initially, but in others, only some are sent out unless snowfall is heavy. Variations in reported times and strategies do not appear to be related to the size or topography of the counties studied.

The average number of hours required per employee (operators and foremen) to remove given amounts of snow in Lake, Eagle and San Juan counties is plotted in Figure 5. (Average number of hours is plotted because in some counties only a portion of the available operators are sent out when snowfall is light.) Lake and Eagle are shown because their reported hours are typical of most counties studied; San Juan is shown because its removal strategy is unique.

All counties studied reported that the effort required to remove snow increases rapidly when snowfall exceeds one or two inches: removing four or six inches of snow requires all operators to work a full day. Removing nine or ten inches requires little more effort than removing six inches, however, since the operating speed of the equipment remains fairly constant. Amounts greater than ten inches were reported to require overtime in all counties studied except San Juan. San Juan uses a two-shift system during larger storms: each employee works an eight hour shift, and the remaining snow is left until the next day.

Average number of hours per employee for mop-up in Lake County, La Plata County, Durango district and Routt County, Steamboat district are plotted in Figure 6. Times for mop-up in these counties, and in the other counties studied increase steadily as snow amounts increase. Unlike times for initial removal of snow, reported mop-up times do not level off for snow amounts between four and ten inches. Times for mop-up do not appear to be related to the size or topography of the counties studied.

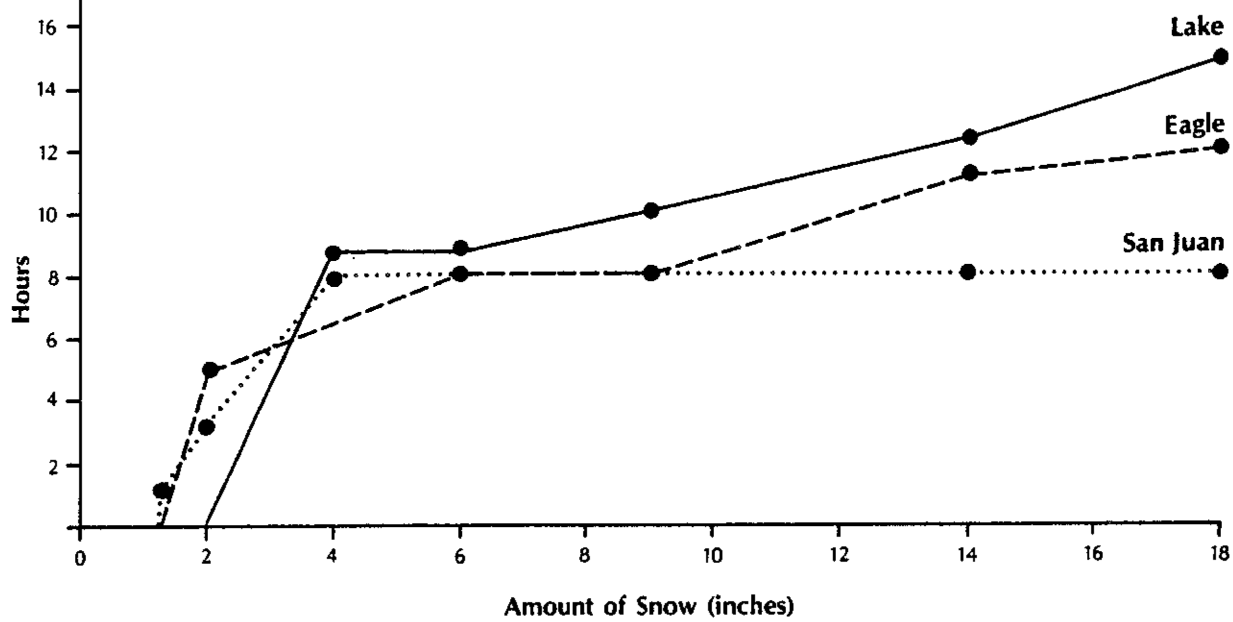

Figure 5. Hours required per employee to remove given amounts of snow in Eagle, Lake and San Juan counties.

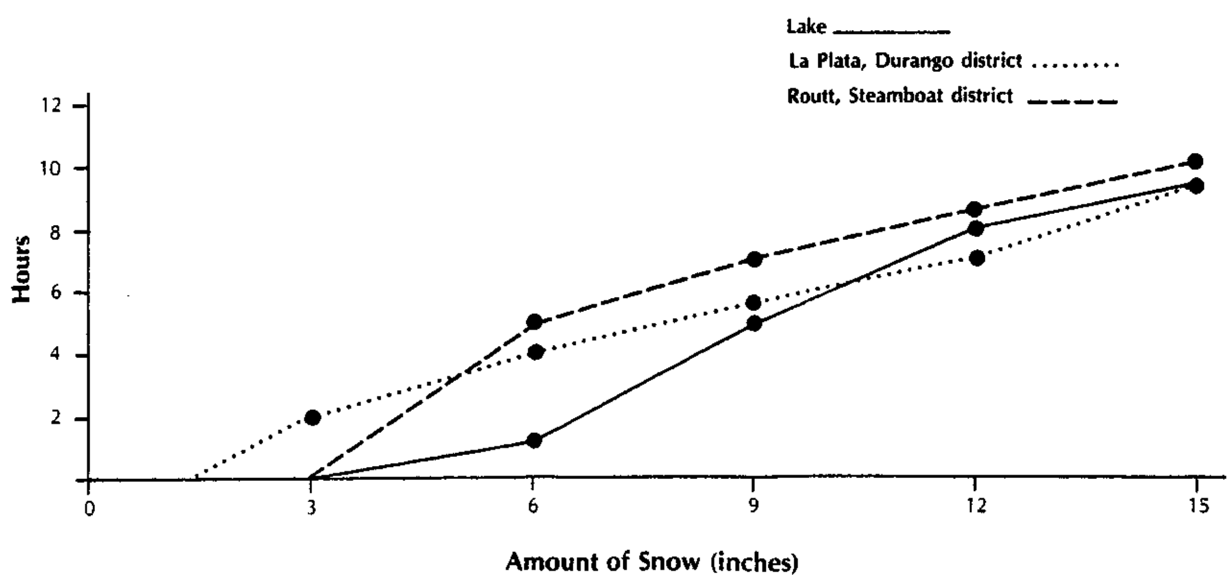

Figure 6. Amounts of snow and average hours per employee to perform mop-up tasks in Lake County, La Plata County, Durango district and Routt County, Steamboat district.

RESULTS

Costs of Removing Snow from Natural Storms

Estimated labor and equipment costs to remove snow from natural storms for winters of low, average and high precipitation in each county studied are shown in Tables 2 through 12. As previously stated, cost estimates do not include wages for office staff, wages when machine operators perform tasks other than snow removal, or expenses for supplies. It is probable, therefore, that actual costs of snow removal are higher than these estimated costs.

If a county is divided into maintenance districts, costs are shown separately for each district. Costs are not computed for districts which do not have a National Weather Service cooperative observer site in or near the town in which the district shop is located. Because some districts were excluded, comparisons of costs by county usually are not meaningful. Estimated total costs per employee were computed to facilitate comparisons across districts with unequal numbers of employees.

Districts were grouped by elevation and topography to explore variations in procedures and costs. Terrain of districts in the "mountainous" group is high and mountainous; terrain in the "non-mountainous" group is lower and flatter. The average elevation of observation sites in the mountainous districts is nearly 2,000 feet higher than the average elevation of sites in the non-mountainous districts. Grouping of districts is approximate because elevation and topography vary greatly within each district.

Estimated equipment costs are greater than labor costs in each winter examined in each district, about one-third greater in La Plata County, Durango district to about twice as great in San Juan County and Garfield County, Glenwood district.

TABLE 2

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--Eagle County**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs ($)			Total Cost ($) Per Employee
			Wages	Machines	Total	
1961-62	80th					
Recorded Snowfall		51.4	16,935	30,077	47,012	2,938
Augmented Snowfall		56.3	18,081	33,260	51,341	3,209
Percentage Increase		9.5%	6.8%	4.4%	9.2%	9.2%
1964-65	50th					
Recorded Snowfall		44.1	7,895	12,527	20,422	1,276
Augmented Snowfall		48.4	8,204	12,854	21,058	1,316
Percentage Increase		9.7%	3.9%	2.6%	3.1%	3.1%
1958-59	20th					
Recorded Snowfall		35.1	9,279	16,373	25,652	1,603
Augmented Snowfall		38.5	10,066	18,019	28,085	1,755
Percentage Increase		9.7%	8.5%	10.1%	9.5%	9.5%

* See page 14.
** 15 operators, 1 foreman.

TABLE 3

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--Garfield County, Glenwood district**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs($)			Total Cost($) Per Employee
			Wages	Machines	Total	
1936-37	80th					
Recorded Snowfall		91.6	20,487	39,926	60,413	6,041
Augmented Snowfall		97.9	20,704	40,487	61,191	6,119
Percentage Increase		6.9%	1.1%	1.4%	1.3%	1.3%
1957-58	50th					
Recorded Snowfall		75.0	15,813	29,840	45,653	4,565
Augmented Snowfall		79.0	16,096	30,362	46,458	4,646
Percentage Increase		5.3%	1.8%	1.7%	1.8%	1.8%
1946-47	20th					
Recorded Snowfall		48.0	9,811	17,661	27,472	2,747
Augmented Snowfall		50.9	10,030	18,020	28,050	2,805
Percentage Increase		6.0%	2.2%	2.3%	2.1%	2.1%

* See page 14.

** 9 operators, 1 foreman.

TABLE 4

Estimated costs to remove recorded and augmented* snowfall in winters of low, average, and high snowfall--Garfield County, Rifle district**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs ($)			Total Cost ($) Per Employee
			Wages	Machines	Total	
1972-73	80th					
Recorded Snowfall		66.9	10,141	16,163	26,304	3,758
Augmented Snowfall		69.9	10,334	16,453	26,787	3,827
Percentage Increase		4.5%	1.9%	1.8%	1.8%	1.8%
1971-72	50th					
Recorded Snowfall		41.6	7,914	13,112	21,106	3,015
Augmented Snowfall		44.6	8,189	13,823	22,012	3,145
Percentage Increase		7.2%	3.5%	5.4%	4.7%	4.7%
1935-36	20th					
Recorded Snowfall		21.1	4,717	8,408	13,125	1,875
Augmented Snowfall		22.5	4,746	8,482	13,228	1,890
Percentage Increase		6.6%	0.6%	0.9%	0.8%	0.8%

* See page 14.
** 6 operators, 1 foreman.

000035

TABLE 5

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--La Plata County, Durango district**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs ($)			Total Cost ($) Per Employee
			Wages	Machines	Total	
1964-65	80th					
Recorded Snowfall		96.5	10,849	14,460	25,309	6,327
Augmented Snowfall		104.5	11,251	15,262	26,513	6,628
Percentage Increase		8.3%	3.8%	5.5%	4.8%	4.8%
1962-63	50th					
Recorded Snowfall		66.0	6,796	9,972	16,768	4,192
Augmented Snowfall		71.3	6,969	10,401	17,370	4,343
Percentage Increase		8.0%	2.5%	4.3%	3.6%	3.6%
1946-47	20th					
Recorded Snowfall		38.1	4,620	6,300	10,920	2,730
Augmented Snowfall		39.8	4,801	6,496	11,296	2,824
Percentage Increase		4.5%	3.9%	3.1%	3.4%	3.4%

* See page 14.

** 3 operators, 1 foreman.

TABLE 6

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--Lake County**

Winter and Percentile of Long-term Seasonal Snowfall	Snowfall (inches)	Estimated Removal Costs ($) Wages	Machines	Total	Total Cost ($) Per Employee
1969-70 80th					
Recorded Snowfall	144.4	20,736	31,358	52,094	5,788
Augmented Snowfall	155.9	22,888	35,795	58,683	6,520
Percentage Increase	8.0%	10.4%	14.1%	12.6%	12.6%
1966-67 50th					
Recorded Snowfall	115.0	16,935	24,549	41,484	4,609
Augmented Snowfall	121.5	18,580	27,913	46,493	5,166
Percentage Increase	5.7%	9.7%	13.7%	12.1%	12.1%
1965-66 20th					
Recorded Snowfall	91.2	15,867	26,645	42,512	4,724
Augmented Snowfall	96.5	16,668	28,323	44,991	4,999
Percentage Increase	5.8%	5.1%	6.3%	5.8%	5.8%

* See page 14.
** 8 operators, 1 foreman.

000037

TABLE 7

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--Ouray County, Ouray district**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs ($) Wages	Machines	Total	Total Cost ($) Per Employee
1978-79	80th					
Recorded Snowfall		160.9	9,377	14,677	24,054	8,018
Augmented Snowfall		170.8	9,615	15,459	25,074	8,358
Percentage Increase		6.2%	2.5%	5.3%	4.3%	4.3%
1967-68	50th					
Recorded Snowfall		145.1	9,336	14,984	24,320	8,107
Augmented Snowfall		151.8	9,547	15,528	25,075	8,358
Percentage Increase		4.6%	2.3%	3.6%	3.1%	3.1%
1950-51	20th					
Recorded Snowfall		124.0	7,633	11,697	19,330	6,443
Augmented Snowfall		130.7	7,810	12,232	20,042	6,681
Percentage Increase		5.6%	2.3%	4.6%	3.7%	3.7%

* See page 14.
** 2 operators, 1 foreman.

000038

TABLE 8

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--Rio Blanco County, Meeker district**

Winter and Percentile of Long-term Seasonal Snowfall	Snowfall (inches)	Estimated Removal Costs ($) Wages	Machines	Total	Total Cost ($) Per Employee
1957-58 80th					
Recorded Snowfall	109.7	76,895	147,082	223,977	7,225
Augmented Snowfall	116.7	81,218	156,928	238,146	7,682
Percentage Increase	6.4%	5.6%	6.7%	6.3%	6.3%
1954-55 50th					
Recorded Snowfall	85.1	52,201	103,279	155,480	5,015
Augmented Snowfall	92.1	55,575	111,469	167,035	5,388
Percentage Increase	8.2%	6.5%	7.9%	7.4%	7.4%
1952-53 20th					
Recorded Snowfall	68.0	45,138	85,412	130,550	4,211
Augmented Snowfall	72.5	46,921	89,736	136,657	4,408
Percentage Increase	6.6%	4.0%	5.1%	4.7%	4.7%

* See page 14.
** 29 operators, 2 foremen.

TABLE 9

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--Routt County, Hayden district**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs ($)			Total Cost ($) Per Employee
			Wages	Machines	Total	
1967-68	80th					
Recorded Snowfall		133.1	25,064	45,150	70,214	7,794
Augmented Snowfall		141.9	26,492	48,593	75,085	8,343
Percentage Increase		6.6%	5.7%	7.6%	6.9%	6.9%
1954-55	50th					
Recorded Snowfall		96.0	15,729	28,091	43,820	4,869
Augmented Snowfall		102.0	16,665	30,668	47,333	5,259
Percentage Increase		6.3%	5.6%	9.2	8.0%	8.0%
1965-66	20th					
Recorded Snowfall		65.0	11,633	20,205	31,838	3,538
Augmented Snowfall		69.7	12,309	22,309	34,707	3,856
Percentage Increase		7.2%	6.6%	10.4%	9.0%	9.0%

* See page 14.
** 8 operators, 1 foreman.

TABLE 10

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--Routt County, Oak Creek district**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs ($)			Total Cost ($) Per Employee
			Wages	Machines	Total	
1949-50	80th					
Recorded Snowfall		136.5	17,997	29,156	47,153	5,239
Augmented Snowfall		143.1	18,985	31,391	50,376	5,597
Percentage Increase		4.8%	5.5%	7.7%	6.8%	6.8%
1957-58	50th					
Recorded Snowfall		118.8	16,141	19,042	35,183	3,909
Augmented Snowfall		128.0	17,137	21,482	38,619	4,291
Percentage Increase		7.7%	6.2%	12.8%	9.8%	9.8%
1971-72	20th					
Recorded Snowfall		87.5	12,819	18,288	31,107	3,456
Augmented Snowfall		95.4	13,043	18,906	31,949	3,550
Percentage Increase		9.0%	1.8%	3.4%	2.7%	2.7%

* See page 14.
** 8 operators, 1 foreman.

TABLE 11

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--Routt County, Steamboat district**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs ($)			Total Cost ($) Per Employee
			Wages	Machines	Total	
1964-65	80th					
Recorded Snowfall		194.7	27,537	50,024	77,561	7,756
Augmented Snowfall		205.7	29,066	53,991	83,057	8,306
Percentage Increase		5.6%	5.6%	7.9%	7.1%	7.1%
1941-42	50th					
Recorded Snowfall		146.9	23,050	37,672	60,722	6,072
Augmented Snowfall		154.1	24,201	40,841	65,042	6,504
Percentage Increase		4.9%	5.0%	8.4%	7.1%	7.1%
1937-38	20th					
Recorded Snowfall		128.4	19,686	30,728	50,414	5,041
Augmented Snowfall		136.3	21,123	34,442	55,565	5,557
Percentage Increase		6.1%	7.3%	12.1%	10.2%	10.2%

* See page 14.
** 9 operators, 1 foreman.

TABLE 12

Estimated costs to remove recorded and augmented* snowfall in winters of low, average and high snowfall--San Juan County**

Winter and Percentile of Long-term Seasonal Snowfall		Snowfall (inches)	Estimated Removal Costs ($)			Total Cost ($) Per Employee
			Wages	Machines	Total	
1948-49	80th					
Recorded Snowfall		203.5	19,317	37,901	57,218	11,444
Augmented Snowfall		218.0	20,194	40,212	60,406	12,082
Percentage Increase		7.1%	4.5%	6.1%	5.6%	5.6%
1949-50	50th					
Recorded Snowfall		143.8	14,654	28,699	43,353	8,665
Augmented Snowfall		152.7	15,360	30,496	45,856	9,172
Percentage Increase		6.2%	4.8%	6.4%	5.8%	5.8%
1975-76	20th					
Recorded Snowfall		123.0	10,509	22,153	32,662	6,533
Augmented Snowfall		130.3	10,772	22,901	33,673	6,735
Percentage Increase		5.9%	0.5%	3.4%	3.1%	3.1%

* See page 14.
** 4 operators, 1 foreman.

Estimated total removal costs per employee range from $1,276 in Eagle County in a winter of average snowfall to $11,444 in San Juan County in a winter of high snowfall. Estimates are generally highest in winters of high snowfall and lowest in winters of low snowfall. Exceptions occurred in Eagle, Lake and Ouray counties: in Eagle and Lake, estimated total costs in the average-snowfall winters examined are lower than those in the low-snowfall winters examined; in Ouray, the estimated total cost in the average-snowfall winter examined is slightly higher than that in the high-snowfall winter examined. These exceptions occurred because the low-snowfall winters in Eagle and Lake and the average-snowfall winter in Ouray had many small storms; small amounts of snow require more time per inch to remove than large amounts.

Estimates of total costs per employee in mountainous districts average 135 percent, 169 percent, and 173 percent of the estimates in non-mountainous districts in the winters of high, average, and low snowfall examined, respectively. These higher costs result, in part, from the greater effort required to clear steep, winding roads. Another reason is that more snow usually falls at higher elevations: snowfall recorded in average-snowfall winters in mountainous districts, averaged 179 percent of that recorded in non-mountainous districts. Klazura (1982) has shown that winter precipitation in the Upper Colorado River Basin is related highly to elevation--more snow usually falls at higher sites than at lower sites.

Costs of Removing Augmented Snow

Estimated costs of removing snow increase when recorded snow amounts are augmented. Increases in costs, shown in Tables 2 through 12 and summarized in Table 13, range from 0.8 percent in Garfield County, Rifle district, in a low-snowfall winter, to 12.6 percent in Lake County in a high-snowfall winter. The average cost increase, over all counties studied, is 6.1 percent in winters of high and average snowfall, and 4.9 percent in winters of low snowfall. Increases in snow amounts are also summarized in Table 13 to allow comparison of snow and cost increases. Increases in costs per employee are shown in Table 14.

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TABLE 13

Summary of estimated increases in seasonal snowfall and removal costs when snow amounts in winters of low, average and high snowfall are augmented*

County (District)	Percentage Increase in Seasonal Snowfall in Winters of Indicated Snow Amounts			Percentage Increase in Removal Costs in Winters of Indicated Snow Amounts		
	High	Average	Low	High	Average	Low
Eagle	9.5	9.7	9.7	9.2	3.1	9.5
Garfield (Glenwood)	6.9	5.3	6.0	1.3	1.8	2.1
Garfield (Rifle)	4.5	7.2	6.6	1.8	4.7	0.8
La Plata (Durango)	8.3	8.0	4.5	4.8	3.6	3.4
Lake	8.0	5.7	5.8	12.6	12.1	5.8
Ouray (Ouray)	6.2	4.6	5.6	4.3	3.1	3.7
Rio Blanco (Meeker)	6.4	8.2	6.6	6.3	7.4	4.7
Routt (Hayden)	6.6	6.3	7.2	6.9	8.0	9.0
Routt (Oak Creek)	4.8	7.7	9.0	6.8	9.8	2.7
Routt (Steamboat)	5.6	4.9	6.1	7.1	7.1	10.2
San Juan	7.1	6.2	5.9	5.6	5.8	3.1
Mean	6.4	6.7	6.6	6.1	6.1	4.9
Mean (excluding highest and lowest)	6.4	6.6	6.5	5.9	5.9	4.8

*See page 14.

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TABLE 14

Increases in removal costs per employee when snow amounts in winters of low, average and high snowfall are augmented*

County (District)	Increase in Removal Costs($) Per Employee in Winters of Indicated Snow Amounts		
	High	Average	Low
Eagle	271	40	152
Garfield (Glenwood)	78	81	58
Garfield (Rifle)	69	130	15
La Plata (Durango)	301	151	94
Lake	732	557	275
Ouray (Ouray)	340	251	238
Rio Blanco (Meeker)	457	373	197
Routt (Hayden)	549	390	318
Routt (Oak Creek)	358	382	44
Routt (Steamboat)	550	432	516
San Juan	638	507	202

* See page 14.

The pattern of percentage increases in costs across winters varies from district to district and does not appear to be related to the wetness or dryness of the winters examined. For example, percentage increases in Routt County, Steamboat and Hayden districts, and Eagle County are highest in low-snowfall winters, while estimated increases in Lake County, La Plata County, Durango district and Ouray County are highest in high-snowfall winters.

Ratios of estimated total removal costs in winters of low and high snowfall to estimated total removal costs in winters of average snowfall are shown in Table 15. These ratios show how increases in costs caused by augmentation (simulated) compare with changes in costs caused by natural variation of snowfall. Costs in winters of low snowfall average 81 percent of costs in winters of average snowfall. Cost ratios above 1.0 in Eagle and Lake counties for the low/average comparison are due, as previously discussed, to many small storms in the winters of low snowfall. Costs in winters of high snowfall average 141 percent of costs in winters of average snowfall. The cost ratio below 1.0 in the Ouray district is caused by the many small storms in the winter of average snowfall.

Mean variations in total costs of 19 percent in low-snowfall winters and 41 percent in high-snowfall winters are well above the average estimated increase in costs of approximately six percent when recorded snow amounts are augmented. This indicates that removal costs probably change more with natural variations in seasonal snowfall than with augmentation.

TABLE 15

Ratios of estimated removal costs of natural snow in winters of low and high snowfall to estimated costs in winters of average snowfall

County (District)	Ratios of Estimated Costs in Winters of Indicated Snow Amounts: Low/Average	High/Average
Eagle	1.25	2.30
Garfield (Glenwood)	.60	1.32
Garfield (Rifle)	.62	1.25
La Plata (Durango)	.65	1.51
Lake	1.02	1.26
Ouray (Ouray)	.79	.99
Rio Blanco (Meeker)	.83	1.44
Routt (Hayden)	.73	1.60
Routt (Oak Creek)	.88	1.34
Routt (Steamboat)	.83	1.28
San Juan	.75	1.32
Mean	.81	1.41

CONCLUSION

Simulating the effects of cloud seeding on the costs of snow removal indicates that costs do increase when recorded snow amounts, in approximately one-third of the storms in selected winters, are augmented 25 percent. The increases in costs range from 0.8 percent to 12.6 percent in the counties studied. Average increases are 6.1 percent in winters of high and average snowfall, and 4.9 percent in winters of low snowfall. Costs in winters of low snowfall average 81 percent of costs in winters of average snowfall, while costs in winters of high snowfall average 141 percent of costs in winters of average snowfall. These variations of 19 percent and 41 percent indicate that costs generally change more with natural variations in seasonal snowfall than with augmentation.

Actual effects of cloud seeding on the costs of removing snow cannot be determined definitively, however, until more accurate records of employee and equipment expenses are available and until atmospheric scientists determine if, and by how much, seeding can increase snowfall. Recommendations for record-keeping include daily accounting of the hours employees spend performing removal tasks, hours machines are used, maintenance costs and fuel consumption.

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APPENDIX

Recommendations for Record Keeping

Counties could determine costs of snow removal more accurately if daily record keeping included:

1. Number of hours each employee spends performing typical tasks (e.g., plowing snow, maintaining machines); and

2. Number of hours each machine is used for various tasks (e.g., clearing snow, hauling cinder), maintenance costs, fuel consumption.

Forms could be designed and procedures developed to make this information easy to collect. Recording accurate costs of snow removal could help counties improve budgeting and planning and also help them develop more efficient procedures for clearing snow.