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PHASE II REPORT

WYOMING WATER DEVELOPMENT OFFICE

CONTRACT 05SC0296808SE

AIRBORNE CLOUD SEEDING IN NORTHERN COLORADO AS AN EXTENSION OF SEEDING OPERATIONS CONDUCTED FOR SOUTHERN WYOMING

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Phase II Report to the
Wyoming Water Development Office

Contract 05SC0296808SE

Airborne Cloud Seeding in Northern Colorado as an Extension of Seeding Operations Conducted for Southern Wyoming

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1. OVERVIEW

The Wyoming Water Development Commission (WWDC), in reviewing means of increasing flows in the Upper North Platte River Basin, recently directed Wyoming Water Development Office (WWDO) staff to implement operational cloud seeding in the Sierra Madre and Medicine Bow Ranges of southern Wyoming. Both ranges contain tributaries that feed into the Upper North Platte River.

As a result of this directive, the National Center for Atmospheric Research (NCAR), Research Application Laboratory (RAL) was contracted to prepare a final design for seeding operations in these two ranges, which were the focal point of the multi-season Wyoming Weather Modification Pilot Project (WWMPP) which evaluated the feasibility of increasing streamflow through ground-based cloud seeding (Breed *et al.* 2014).

The Final Design study for these two ranges (NCAR 2017) provides some background for this study, which explores the requirements, in facilities and cost, to extend airborne operations as described in that study southward, into northern Colorado (Figure 1). The motivation is two-fold. First, the North Platte Basin Round Table (NPBRT), a water-users organization within the Colorado portion of the Upper North Platte drainage, expressed interest in implementing seeding as an add-on to activities being explored by the WWDO. Secondly, the Upper North Platte flows north into Wyoming, and the basin as a whole is chronically water-short.

Figure 1. The Never Summer Mountains are pictured as they appeared on January 18, 2018. The picture was taken from just south of Walden, Colorado.

The cost estimates provided for Wyoming operations in the NCAR (2017) report are also modified herein, to reflect more current pricing, and also the use of a more robust seeding aircraft, capable of more lengthy flights and carrying more seeding material. In addition, this aircraft, a turbo-prop (prop-jet, rather than a piston-engine aircraft) can safely operate longer in aircraft icing conditions, commonly encountered while seeding.

The ranges of interest to the NPBRT are those of the Upper North Platte River surrounding the town of Walden, Colorado: the southern Medicine Bow Range and Never Summer Range (east, pictured in Figure 1), the Park Range (west), and the Rabbit Ears Range (south). The relative positions of these ranges are shown in Figure 2.

The balance of this report examines how and when seeding flight could be extended into Colorado, the cost of such efforts, and how such an effort could be evaluated.

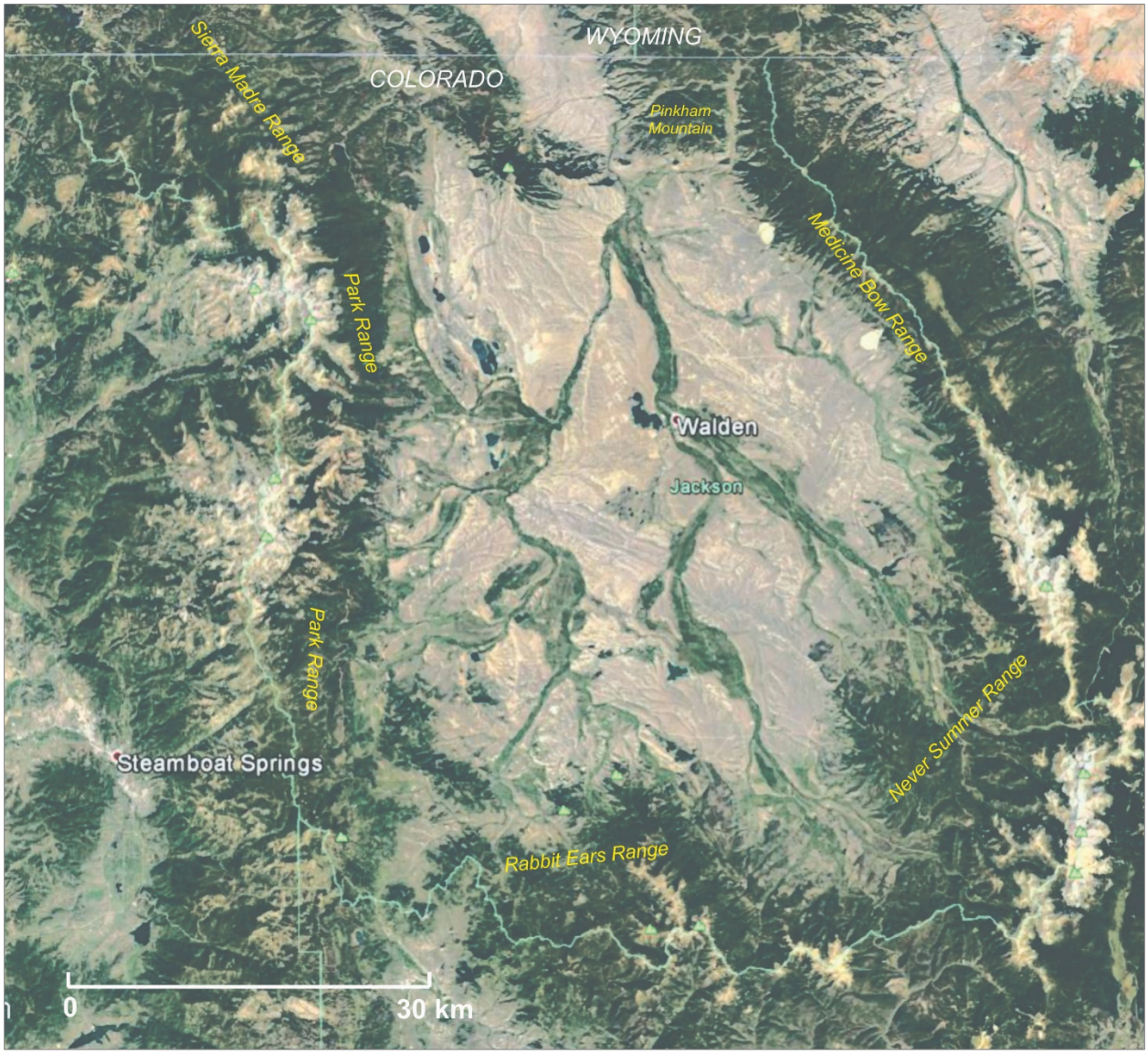

Figure 2. The potential target ranges in Colorado are shown, each bordering the Upper North Platte River Basin within Colorado. Which range(s) are targeted on any given day would depend upon prevailing wind direction, cloud conditions, and the availability of the seeding aircraft. *Image courtesy of Google Maps.*

2. SCOPING MEETINGS

The potential scope of the expansion into Colorado was initially established through informal discussions between a few stakeholders in the Upper North Platte Basin who reside near Walden, Colorado, and staff of the WWDO.

2.1 Walden, Colorado

A follow-on conversation involving Weather Modification International (WMI) staff, a representative from the Colorado Water Conservation Board (CWCB), and a scientist from Heritage Environmental Consultants occurred in mid-January 2018.

Through these initial meetings level of interest and possible funding mechanisms were discussed, and input from the CWCB weather modification permitting authority was received.

Because the add-on of operations in Colorado would likely pay only for flight time and seeding agent in Colorado, it was acknowledged the seeding operations could occur in Colorado when weather conditions were favorable in Colorado but not Wyoming, as the deployment costs will be paid by Wyoming. However, the number, frequency, and scale of operations in Colorado were discussed only in general terms. Sections Three, Four, and Five of this report describe in more detail how such a collaborative effort might work, and include cost estimates.

2.2 Cheyenne, Wyoming

At a meeting of the Wyoming weather modification Technical Advisory Team (TAT) in early February 2018, the preliminary results of this study were presented, including the potential flight tracks. Two representatives from the NPBRT attended, as well as Mr. Joe Busto, who handles weather modification permitting for the CWCB.

The possibility of expanding the operations being planned for south-central Wyoming mountains was presented to the TAT, including the requirements for initiating cloud-seeding programs in Colorado.

This project would be unique to Colorado because though a number of wintertime cloud-seeding programs are ongoing in that state, none of these is airborne. Colorado regulations, while very similar to those of Wyoming, are worded slightly differently for ground-based and airborne operations, so there may be differences in the administration of any such program. A final determination has not yet been made.

Colorado regulations also require annual payment of a “Commercial Fee” for any cloud-seeding activities that are not specifically for research purposes (see section 4). This fee is 2% of the actual funds expended in conduct of the seeding operations, and is to be paid at the conclusion of each season. This fee, collected by the CWCB, remains with that agency and is used for project administration.

3. AIRCRAFT TRACKS FOR COLORADO CLOUD SEEDING

Potential flight tracks for airborne seeding of the Medicine Bow and Sierra Madre Ranges in Wyoming are shown in Figure 3. Sample flight tracks for operations in Northern Colorado have also been added. Flight tracks are designed to effectively target the desired mountain ranges, to be perpendicular to storm wind direction, and account for a variety of wind speeds, thus the varying orientations. For example, MB5 would be used for lighter westerly winds and MB4 and MB3 for higher winds speeds, while MB1 and MB2 would be used for northerly winds.

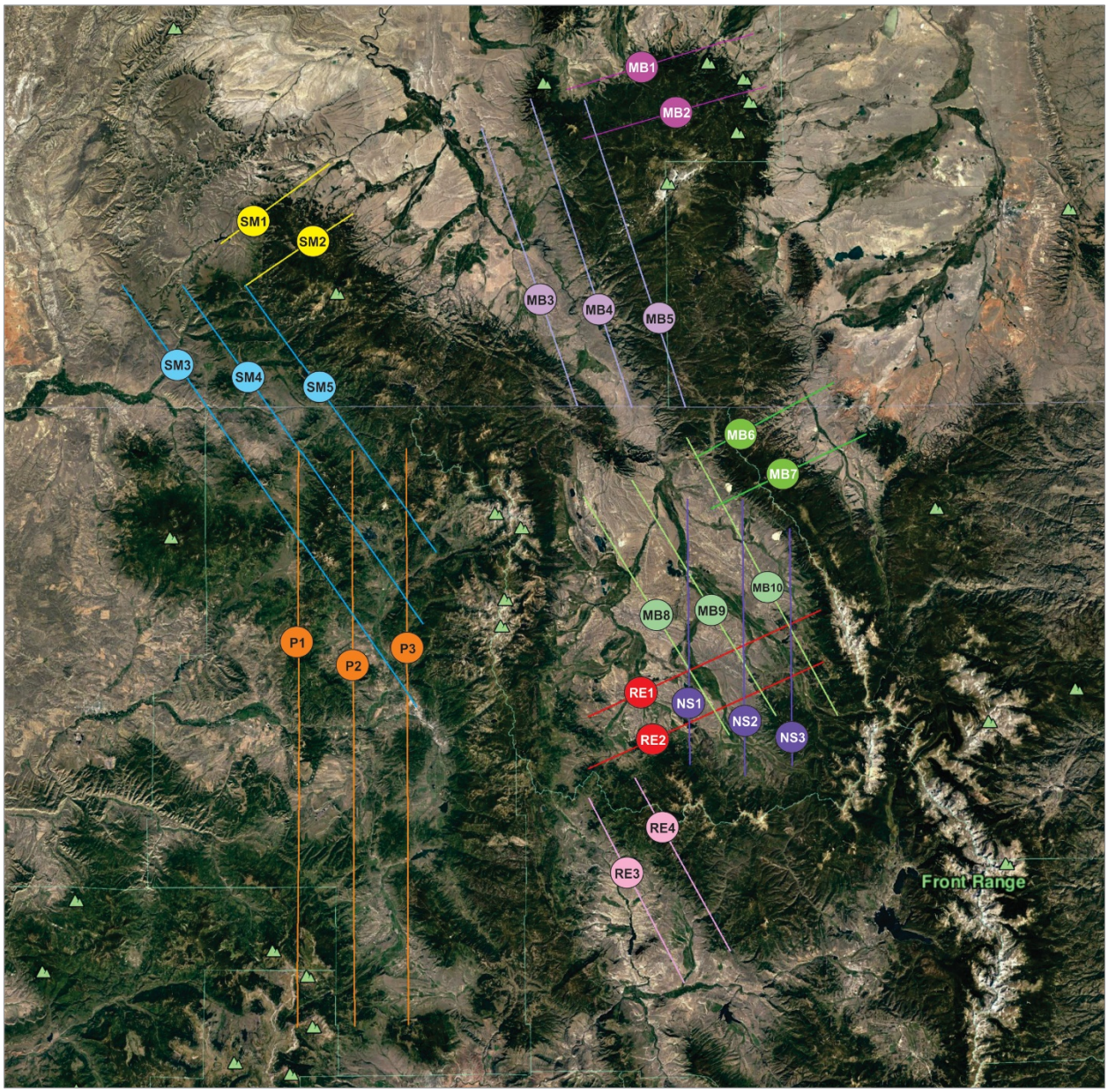

Figure 3. Approximate locations of flight tracks that could be used for airborne seeding are shown. Each color-group represents tracks that would be flown for a specific wind direction; for each; the track closest to the target range would be used with lighter (slower) winds, that farthest away, stronger winds. The letters indicate the range targeted by each: MB for Medicine Bow, NS for Never Summer, P for Park, RE for Rabbit Ears and SM for Sierra Madre.

For any given wind direction and speed, the cloud seeding team will select the track(s) most appropriate, to ensure effective targeting of those project mountain ranges having clouds suitable for glaciogenic seeding. Not all possible tracks are shown, and those shown may be revised as dictated by actual site-specific experience. The flight crew routinely changes tracks during the course of seeding missions when the wind direction and/or speed changes.

Some flight tracks as shown in Figure 3 are fairly lengthy, for example: MB3, MB4, MB5, SM3, SM4, SM5, and especially P1, P2, and P3. Effective targeting depends on achieving more-or-less continuous coverage of seeding material, so when winds are strong, seeding agent is quickly transported downwind, and the aircraft must reverse course more often to avoid gaps in coverage. This means that the length of the flight track is effectively shortened. Thus, for these longer tracks, the flight crew will most times focus on the *best* seeding conditions, and fly repeatedly those portions of the tracks where optimal seeding conditions are found. An example of an actual airborne seeding flight track (from another WMI program) is provided in Figure 4.

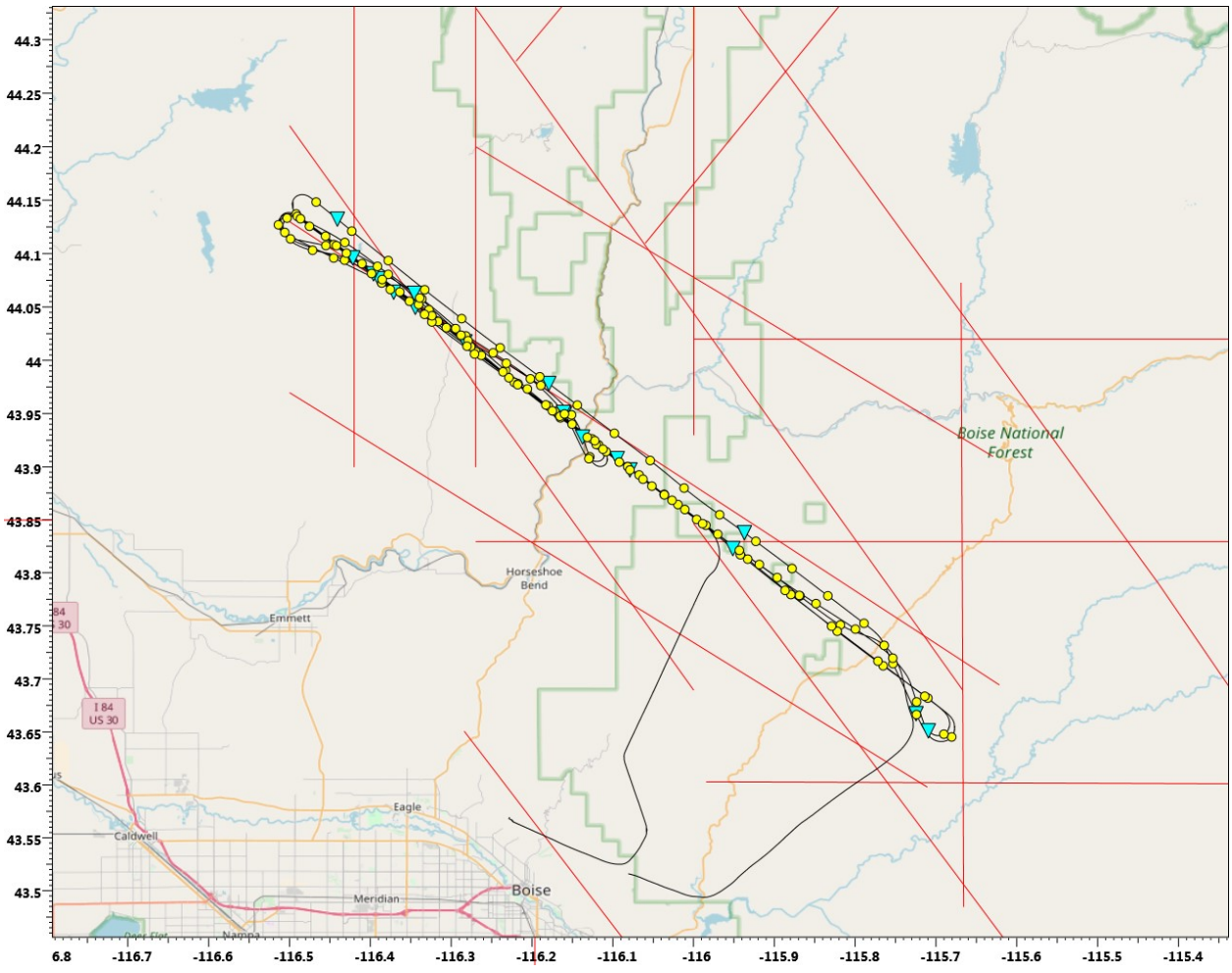

Figure 4. Flight tracks (red lines) analogous to those illustrated in Figure 3 are shown for an existing WMI wintertime seeding program. The actual path of the aircraft flown on this seeding mission is plotted (black line) from GPS positioning, and superimposed upon the track the locations where 20-gram ejectable flares were dropped (yellow dots) and where burn-in-place flares were ignited (blue triangles). All these events are time-resolved as well.

4. WEATHER MODIFICATION CLOUD SEEDING PERMIT REQUIREMENTS FOR COLORADO

Mr. Joe Busto, who handles weather modification permitting, reporting, and evaluation for the Colorado Water Conservation Board (CWCB), a division of the Colorado Department of Natural Resources (CDNR), indicates that all projects conducted in Colorado must receive an annual seeding permit. When a program is begun, public hearings are required wherein persons can express their support or concerns, which then become a matter of public record. Seeding in the Upper North Platte River Basin within Colorado would thus require such hearings, which are administrated by the CWCB.

4.1 Permit Fee and Notice of Intent to Modify Precipitation

When a permit application is filed with the CWCB, a one-time $250 fee is paid. Within 45 days of receipt, the CWCB will complete a review. If the requirements for permit issuances are satisfied, the CWCB will notify the contractor that legal Notices of Intent to Modify Precipitation can be published in the affected target area counties, and also in those counties adjacent to the target area. Such notices are to be published in the official county newspaper, or if such newspaper is published infrequently (less often than weekly) another, more-widely read paper within the affected area. Publication must occur in two consecutive weeks, include a brief synopsis of the proposed program, and the location, time, and date, of a public hearing, to be conducted within two weeks of the last publication date.

4.2 Hearing

Prior to permit issuance, the hearing is conducted within the project area. While such a hearing is administered by the CWCB, the primary purpose is to provide the contractor an opportunity to explain the project to those in attendance. Typically, a presentation is given during which the requirements of the Colorado permit are addressed. A question and answer session follows, and after that, time for anyone to state, for the record, their support or concerns.

After the hearing has been completed, the information gathered is processed by the CWCB, and a decision made as to whether or not the project should proceed.

4.3 Commercial Fee

For all weather modification operations conducted within the State of Colorado except those solely for research purposes, a 2% fee is assessed, based on the total amount expended on the operations during the season (CWCB 2012). This fee is paid after the season has been completed.

4.4 Evaluation

Current CWCB weather modification rules (CWCB 2012) also require that seeding programs in the state be evaluated annually. Most commonly, this is done by comparing historical (periods with no seeding) precipitation records from within the target area to those outside it, and then during seeded months, repeating the comparison to see if a difference is observed. Typically, precipitation data from existing Natural Resources and Conservation (NRCS) snow telemetry (SNOTEL) sites are used. A map of existing SNOTEL sites (Figure 5) suggests that there is likely a number of options available.

To gain an understanding of the costs of such an evaluation, North American Weather Consultants (NAWC) was contacted, which does such evaluations for several of the existing Colorado programs. Mr. Don Griffith, NAWC Principal, shared (personal communication) that costs are front-loaded, with the set-up of the evaluation protocol, choice of target and control sites, and statistical methodology being established.

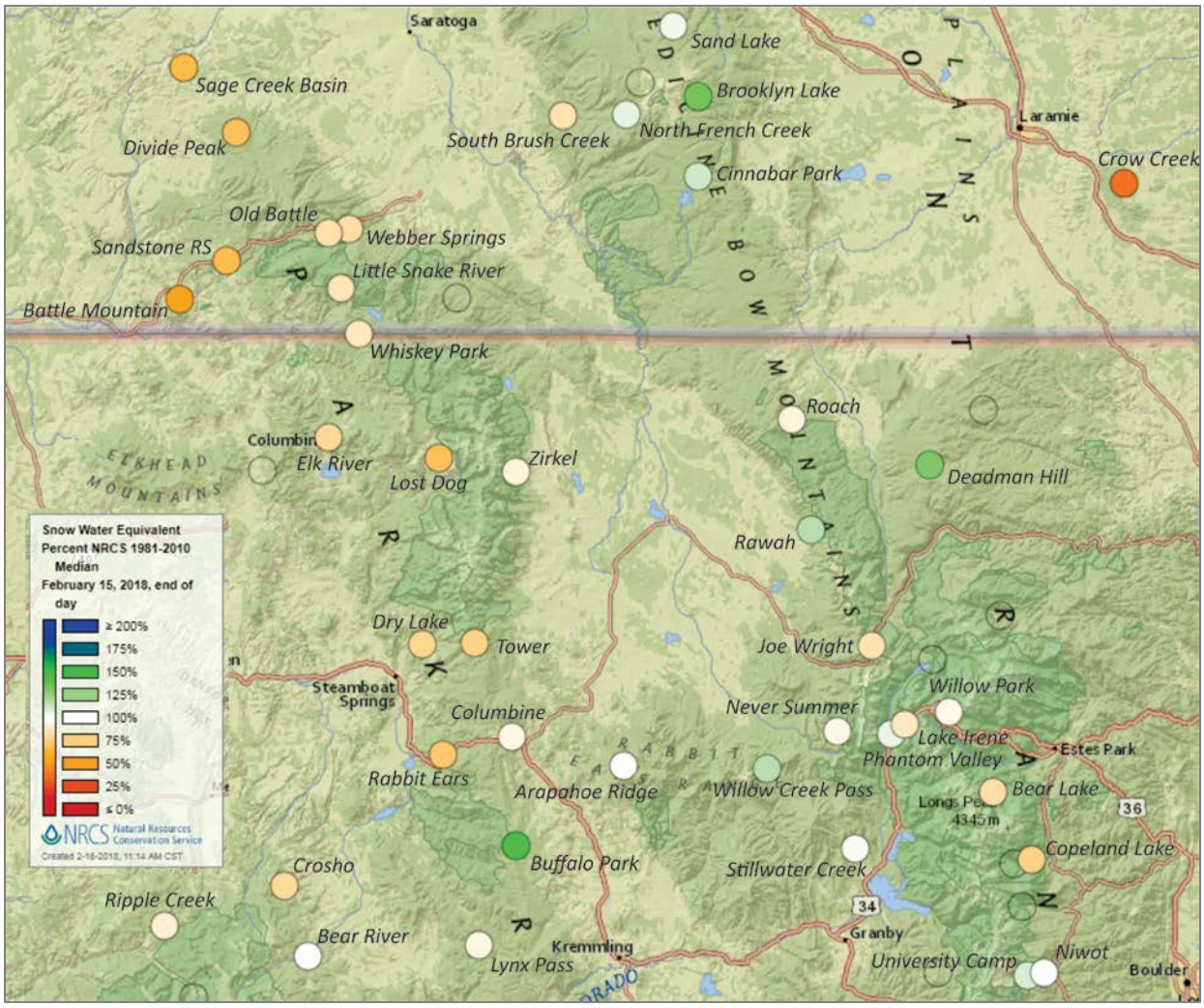

Figure 5. The locations and range of snow water equivalents (SWE) at each of the SNOTEL sites in the ranges of interest are shown, as of February 15, 2018.

This initial cost, Griffith said, is typically $35,000. For subsequent seasons, however, the choices and procedures initially developed can be used, so costs drop markedly, to approximately $5,000. If the gauges initially chosen for the evaluation remain functioning, the cost in subsequent seasons remains near the $5,000 level.

5. COST ESTIMATES

In preparing cost estimates for an airborne seeding program that would embrace the Upper North Platte basin in Wyoming and Colorado, the type of aircraft was revisited. In the NCAR (2017) report on the final design for seeding in the Medicine Bow and Sierra Madre Ranges of Wyoming, costs for airborne seeding were predicated on a smaller total target area, excluding Colorado, and thus quoted approximate costs at that time for a pressurized, twin-engine piston aircraft, a type often used for smaller target areas.

More recently, the WWDO has indicated to those conducting this study that some seeding in the Laramie Range, farther north, might also be expected. With such a large potential target area, longer flight times become almost a necessity. Thus, this report provides estimates based on a more robust seeding platform with longer on-station time, greater speed and performance, and also the capability to carry and use more seeding agent. Table 1, comparing the two aircraft types, is given below.

TABLE 1. Comparison of Twin Piston-Engine and Twin Turboprop Seeding Aircraft

	Seeding Agent Payload			*Engine Horse-power*	*On-Station Time (hours)*		*Rate of Climb (fpm)*		*Cruise Speed (knots)*	*Approximate Distance Flown in a Typical Flight (miles)*
	Burn-in-Place Flares (150g each)	*Ejectable Flares (20g each)*	*Total Payload (grams)*		*Minimum to Maximum*	*Typical*	*In Normal Flight Conditions*	*In Icing Conditions*		
Cessna 340 (twin piston)	24	306	9720	325	1 to 3	2	500-800	<500	170	340
King Air C90 (twin turboprop)	48	306	13320	550	3 to 5	4	1000+	500-1000	230	920

When seeding winter orographic clouds, two types of glaciogenic pyrotechnics can be used, both of the same formulation. One type, the "burn-in-place", or BIP pyrotechnic, is burned while affixed to the aircraft. These flares are used while flying within cloud or just skimming the supercooled cloud tops. They may also be used flying upwind of target clouds when wind flow will carry the ice nuclei thus produced into the supercooled portion of the clouds. Since nothing is dropped from the aircraft, there is no restriction regarding vertical separation from the terrain below; they can be used at any time and location. The BIP, which contains 150 grams of seeding agent and burns for about 4 minutes, is thus the more versatile of the glaciogenic pyrotechnics.

Figure 6. A WMI King Air C90 is pictured, with flight crew, on another current winter orographic seeding program in the Rocky Mountains of the Northern U.S. The burn-in-place flares can be readily seen behind the wing (right). *WMI photograph by Brook Mueller.*

The second type of glaciogenic flare is the smaller "ejectable", or EJ, pyrotechnic. These 20-gram flares are simultaneously ignited and ejected from the aircraft. In the course of their nominal 37-second burn time, they fall about 3,000 feet (~ 1.0 km) before burning completely. Nothing survives to the ground. As they burn and fall, they create a vertical "line" of ice nuclei that quickly treats a depth of cloud. Because they fall about 3,000 feet, ground clearance must be at least that; typically at least 4,000 feet of separation is desired. They are very useful

when the supercooled cloud layer is deep, and also when aircraft icing is heavy (rapid) enough to necessitate flight above the supercooled cloud top.

In addition to the seeding payload advantage, the turboprop C90 also is faster in rate-of-climb and cruise speed, and has about two hours more on-station (seeding) time. That aircraft will thus spend a greater of its flight time at altitude and seeding, rather than in flight to and from target areas. Finally, the greater engine power means that when aircraft icing is encountered, the aircraft is better able to deal with it and remain in position, seeding. [This does not mean that the aircraft can carry unlimited ice, but that the aircraft has the power to climb above (and use EJ flares), or to continue the flight longer in light icing conditions (when build-up is slow).]

The aircraft could be based in Laramie or Cheyenne, depending upon availability of hangar space. Deicing, necessary when an aircraft has snow or ice on it before takeoff, is expensive and time-consuming, so having dependable hangar space is essential. The estimated costs of various-length winter orographic seeding programs *for the Medicine Bow and Sierra Madre Ranges of Wyoming only* are given in in Table 2.

TABLE 2. Wyoming Airborne Seeding Cost - King Air C90

		Cost	Cost Per Month	Length of Operations		
				4 months	5 months	6 months
Mobilization and Demobilization	Personnel	$ 7,271				
	Direct Costs	$ 15,197				
Operations	Personnel		$ 35,711.85	$ 142,847.41	$ 178,559.26	$ 214,271.11
	Direct Costs		$ 28,303.36	$ 113,213.44	$ 141,516.80	$ 169,820.16
Expendables and Other Reimbursible Costs			$ 38,784.00	$ 155,136.00	$ 193,920.00	$ 232,704.00
Estimated Total Costs, Operations Only:			**$ 102,799.21**	**$ 411,196.85**	**$ 513,996.06**	**$ 616,795.27**
Estimated Total Costs Including Mobilization:				**$ 433,664.85**	**$ 536,464.06**	**$ 639,263.27**

Costs shown in Table 2 are broken into two categories: mobilization and operations. Mobilization/demobilization costs are fixed and do not change with varying project length. In proportion to the operations they are small because only the aircraft and some support equipment needs to be readied and moved to the project site. The operations crew consists of three persons, a flight crew of two and a support meteorologist. Technical support is provided from Fargo, and maintenance, if needed, is handled locally. Operations costs are shown for three categories: personnel, direct costs, and expendables. Aircraft fuel is included in the "expendables and other reimbursable costs", along with seeding agent, flight hours, and local travel (lodging, per diem).

Included in the operational personnel cost estimate is $11,900 (monthly) for around-the-clock meteorological support. Such support for forecasting support, weather monitoring, and dispatch of aircraft is necessary. However, we here note that if the contractor has other programs in the vicinity such costs may be effectively shared, resulting in significant savings.

It is recommended that if a four-month program is funded, the months of December, January, February, and March would be best from a climatological standpoint. If a program would be of five months duration, then two weeks should be added on each end. If six months can be managed the project could begin November 1st or November 15th. Aircraft seeding affords the capability to seed deeper clouds that may be too warm in lower levels (targetable by ground seeding) but are sufficiently cold aloft. Such conditions typically occur more frequently in fall and spring.

The additional cost incurred by Colorado participation are shown in Table 3.

TABLE 3. Costs of Extending Operations Into Colorado

Project Administration - Notices, Hearings, Fees, etc.	***First Season***	***Subsequent Seasons***
Notices of Intent	$ 1,000	$ 1,000
Hearing Costs	$ 1,500	$ 1,500
Permit Fee	$ 250	$ -
Commercial Fee (2% of Contract Cost)	$ 1,320	$ 1,320
Subtotal, Project Administration:	***$ 4,070***	***$ 3,820***
Evaluation Costs		
Set-up & 1st Season, Target-Control Analysis (using SNOTEL data)	$ 35,000	
Annual Evaluations (subsequent seasons)		$ 5,000
Subtotal. Evaluation:	***$ 35,000***	***$ 5,000***
Permitting		
Assistance with Completion of Permit Application	$ 1,500	$ 1,500
Operations Costs	***QTY***	***Cost***
Flight Hours[1]	15	$ 5,250
Fuel[2]	1200	$ 4,800
Seeding Agent - Burn-in-place Pyrotechnics[3]	108	$ 8,964
Seeding Agent - Ejectable Pyrotechnics[4]	200	$ 6,400
Subtotal, Operations:		***$ 25,414***

Flight hours (dry) @ $350.00 per hour
Fuel billed at actual cost, presently $4.00/gal
Burn-in-place Pyrotechnics (150 grams each @$83)
Ejectable Pyrotechnics (20 grams each @$32)

TOTAL ESTIMATED PROJECT COSTS	***First Season***	***Subsequent Seasons***
Administration:	$ 4,070	$ 3,820
Evaluation:	$ 35,000	$ 5,000
Permitting:	$ 1,500	$ 1,500
Operations:	$ 25,414	$ 55,760
TOTAL ESTIMATED COSTS, SEASONS ONE and TWO:	***$ 65,984***	***$ 66,080***

Because of the costs of establishing the evaluation procedure required by state regulations, actual flight operations in Colorado would be somewhat limited during the initial season, as shown in the Operations Costs within Table 3. However, after the initial season this would change significantly, as the funds used for establishing the evaluation protocol could be shifted in operations. The amount thus available for actual seeding would jump from $25,000 the first season to nearly $56,000 the second.

A potential second-season breakout of operational costs is given in Table 4. Thus, the operational effort in Colorado could potentially double.

TABLE 4. Second-Season Colorado Operations

Item	*Quantity*	*Cost*
Flight Hours	32.0	$ 11,200
Fuel	2560	$ 10,240
BIP Flares	240	$ 19,920
EJ Flares	450	$ 14,400
Totals		***$ 55,760***

These estimates of costs for operations in Colorado have been developed in consultation with Colorado Water Conservation Board staff, and reflect costs at the time (February 2018). Some costs may vary, for example, the price of aircraft fuel or that of seeding agent.

6. SUMMARY

A means has been presented through which airborne cloud seeding operations in the Medicine Bow and Sierra Madre Mountains of Wyoming, and also for adjacent ranges surrounding the Upper North Platte River Basin in Colorado are possible. Operations for Wyoming could be readily expanded to include the Park, Never Summer, and Rabbit Ears Ranges of Colorado.

The use of a turboprop aircraft would add the performance and on-station time needed to serve an expanded target area, in addition to having a greater seeding payload than would be available on a piston-engine aircraft. The added performance also brings a greater safety margin during flights in icing conditions. Curiously, the supercooled cloud water (SLW) that causes aircraft icing is also an essential ingredient for effective glaciogenic cloud seeding. Thus, a good seeding mission requires SLW, but also the ability to safely deal with it!

Not addressed in this report but necessary for the inclusion of Colorado is the development of a protocol through which the selection of target area (Wyoming or Colorado) will be made on a day-by-day and case-by-case basis. Seeding suspension crtieria also need to be established in advance. These are beyond the scope of this report, but must be done before operations begin.

All airborne seeding events (the firing of an EJ pyrotechnic or the lighting of a BIP) should be recorded by an on-board data logger, so a precise record of all seeding can be obtained from each flight. From it, the evaluation required by the CWCB described in Section 4 would be possible. Likewise, the location of each flare fired and ignited could readily be sorted by target area, i.e., Wyoming or Colorado. Such flight tracks (see the example in Figure 4) need to be part of the seeding record, and included in the reporting.

7. GLOSSARY OF TERMS AND ACRONYMS

BIP – a burn-in-place glaciogenic cloud seeding pyrotechnic (flare), 150 gram yield
CDNR – Colorado Department of Natural Resources
CWCB – Colorado Water Conservation Board, a division of the Colorado Department of Natural Resources and Conservation (CDNR)
EJ – an ejectable glaciogenic cloud seeding pyrotechnic (flare), 20 gram yield
NAWC – North American Weather Consultants
NCAR – National Center for Atmospheric Research, Boulder, Colorado
NPBRT - North Platte Basin Round Table
NRCS – Natural Resources Conservation Service
RAL – Research Applications Laboratory, a part of NCAR
SLW – supercooled liquid water
SNOTEL – Snow Telemetry, a snow gauge network operated by the NRCS
SWE – Snow water equivalent
TAT – Technical Advisory Team, created as part of the WWMPP
WMI – Weather Modification International, business name for Weather Modification LLC, Fargo, North Dakota
WWDC – Wyoming Water Development Commission, the State body directing the WWDO
WWDO – Wyoming Water Development Office
WWMPP – Wyoming Weather Modification Pilot Program

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