FEASIBILITY/DESIGN STUDY FOR A CLOUD SEEDING PROGRAM IN THE YADKIN RIVER BASIN, NORTH CAROLINA

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ABSTRACT

North American Weather Consultants (NAWC) was contracted by Cube Hydro Partners, LLC with headquarters in Bethesda, Maryland, to conduct a cloud seeding feasibility/design study for the Yadkin River Basin located in North Carolina. This study was prepared in conformance with American Society of Civil Engineers’ Guidelines and Standards. The goal of the program would be to augment precipitation over the Yadkin River Basin to increase streamflow into a series of Cube Hydro reservoirs along the Yadkin River. This increased streamflow would then be used to generate additional hydropower (clean energy) from facilities installed on project dams. NAWC compiled a site-specific climatology for this Basin. Both ground-based and airborne seeding was considered, but only airborne seeding was recommended due to the lack of significant topographic features in the Basin, the rather high average height of the -5 °C level in potentially “seedable” storms (630 mb), and other meteorological factors. Regression equations relating precipitation to streamflow suggest that seeding during the cool season would also have a residual effect that increases streamflow throughout the entire year and not just during the cool season. Overall, cool-season seeding is likely to have about 1.4 times as much impact on total streamflow as warm-season seeding (assuming the same percentage increase in precipitation), with the cool season increase more evenly distributed throughout the year in terms of the resultant streamflow. Therefore, only a cool season program was recommended. Detailed examination of a 3-year cool season storm climatology in the Yadkin Basin suggests that aircraft-based cloud seeding during the cool season could enhance precipitation by 4.1%, resulting in an estimated 5.2% increase in annual streamflow (109,200 acre-feet). Cost estimates were prepared for a seasonal program. Once the estimated costs were established, NAWC was able to develop benefit/cost ratio estimates. Using information provided by Cube Hydro, NAWC calculated a potential benefit/cost ratio of 5/1. NAWC concluded that the proposed program was feasible based upon both technical and economic considerations as recommended in the “Guidelines for Cloud Seeding to Augment Precipitation”, Third Edition by the American Society of Civil Engineers (ASCE, 2016).

1.0 INTRODUCTION

North American Weather Consultants (NAWC) was contracted by Cube Hydro Partners in September 2018 to conduct a cloud seeding feasibility/design study for the Yadkin River Basin located in North Carolina. Cube Hydro, with headquarters in Bethesda, Maryland, owns reservoirs with hydropower production capabilities in several eastern states. This study was conducted in conformance with American Society of Civil Engineers’ (ASCE) Guidelines (2016) and Standards (2017). Cube Hydro owns four reservoirs along the Yadkin River. Each dam is equipped with turbines to generate hydropower.
Figure 1 provides a map of the Yadkin River Basin above the Cube Hydro Reservoirs, which would be the intended target area of the cloud seeding program. This figure also provides the locations of precipitation and streamflow gauges that were used in subsequent analyses. The goal of the program would be to increase precipitation over the Yadkin Basin upstream of the Cube Hydro’s Reservoirs, which in turn would increase streamflow into the reservoirs. This increased streamflow could then be used to generate additional hydropower, a clean energy source. Topics that NAWC addressed in conducting this study included: cloud seeding theory, prior studies, climatology, storm period analysis, estimates of seasonal increases in precipitation and streamflow, development of a program design, establishment of operational criteria, communications and reports, evaluation of seeding effects, cost estimates, benefit versus cost estimates, environmental considerations, general legislative considerations, permit and reporting requirements and preparation of a final report.

2.0 TARGET AREA CLIMATOLOGY

The Yadkin Basin receives consistent precipitation throughout the year, with an annual average just over 46" for eight representative precipitation sites (locations shown on Figure 1). These annual averages range from about 42-44" on the lower eastern edge of the watershed to between about 48-56" along the higher and more mountainous western edge. Seasonally, the October – February period is the driest and the July – September period is the wettest. Figure 3 provides a plot of the average monthly precipitation at the eight precipitation sites.
Data were collected for representative storm periods in the Yadkin Basin during three cool seasons (2015-16, 2016-17, and 2017-18). Analyses of these storm periods utilized Greensboro (GSO) upper-air rawinsonde (RAOB) soundings that were considered representative of precipitation periods during the November – April cool season. The Greensboro upper-air sounding site is located just east of the intended target area as shown in Figure 1. A later section on estimated precipitation increases and resulting estimates of streamflow increases will explain the focus on the cool season. For the three analyzed seasons, data were collected from 123 storm period soundings. These data were also paired with surface observations from the Greensboro (KGSO) airport to identify precipitation periods and associated precipitation rates near the time when the sounding data were observed. These were 6-hour periods centered on the sounding times and for periods that a meteorologist judged to have no substantial atmospheric changes. These storm periods were then analyzed to estimate their “seedability” based upon cloud top temperatures and pilot reports of icing in the area. Previous research programs have shown that winter storm periods with cloud top temperatures less than approximately -22 °C to -25 °C typically contain little if any supercooled liquid water, are naturally efficient in producing precipitation and therefore have little if any seeding potential (Griffith, et al., 2013; Hill, 1980; Reynolds and Dennis, 1986; and Reynolds, 1988). In selecting the above storm periods for analysis, the Greensboro rawinsonde data were used to estimate cloud top temperatures. 

Pilot reports of icing indicate the presence of supercooled (colder than freezing) cloud droplets which are the targets of glaciogenic cloud seeding programs. For each case, based on the sounding data and associated pilot reports, a percentage estimate was made of potential seeding increases using cloud seeding aircraft. In some cases, no potential increase due to seeding was anticipated. Other storm period estimates ranged from approximately 3% increases for some of the marginal cases, to approximately 10% in some of the better situations (especially those involving convective activity). The resulting (precipitation weighted) average increase for all these estimates was 4.1%. The analysis results show that about 84 of the 123 soundings (68%) examined during these storm periods were determined to have at least some seeding potential. This 68% statistic should be representative of the cool-season period.

An ideal seeding zone, utilizing silver iodide as the seeding agent, was assumed to be between -5 °C to -15 °C. This “seedable” zone typically ranges between approximately 675 mb (11,000 feet) and 550 mb (16,000 feet) in these storms, although there are some lower outliers during a few colder events. The average (mean) height of the -5 °C level (the most common level for cool season aircraft seeding operations) was 632 mb for all the cases that were considered to have cloud seeding potential, with a corresponding median value of 620 mb. These mean/median -5 °C levels are generally near 13,000 feet in altitude. Based upon the height of this level and the relatively low elevations of the Yadkin Basin, NAWC determined that only airborne seeding would be considered due to the considerable distance that silver iodide nuclei would need to travel vertically from ground level to the -5 °C level, the threshold activation temperature of silver iodide. It was also found that the “seedable” zone had strong winds, averaging between 40 – 60 knots during these events. Wind speed and direction do not affect the efficiency of cloud seeding processes, but do affect the targeting of seeding effects to impact the intended target area. Figure 2 provides a wind rose of wind direction and speed at the -5 °C level during “seedable” events. Winds from the southwest direction are prominent, which indicates that these cool season precipitation events primarily occur in pre-upper trough passage (warm sector) conditions that at least partially explain the relatively high -5 °C level during these events.

Meteorologically, it is evident with most of these cool season storm periods in which significant precipitation was observed that a warm, moist air mass originating to the south and southwest,
typically near the Gulf of Mexico, was being lifted over a cooler air mass residing in the lower levels of the atmosphere over the eastern U.S. landmass. One consistent indication in the analyzed storm periods was a zone of strong thermodynamic stability in the lower levels of the atmosphere, from near the surface extending up to approximately 4,000 to 6,000 AGL. Temperatures were often inverted in the lower levels (a very stable situation), with a temperature maxima of 3,000 to 4,000 feet MSL being relatively common. This type of thermodynamic stability would prevent significant vertical mixing in the lower levels of the atmosphere, a situation that would further preclude any effective ground-based seeding, as the seeding material would remain trapped in the lower levels of the atmosphere.

3.0 ESTIMATES OF SEASONAL INCREASES IN PRECIPITATION AND STREAMFLOW

Eight precipitation sites were initially selected based on data availability (monthly precipitation totals), distributed in and around the watershed, and individual correlations with streamflow data. Locations of these gauges are provided in Figure 1. Monthly precipitation data for these sites were obtained from the National Weather Service (NWS/NOAA) and the National Climatic Data Center (NCDC). Two unregulated tributary stream gauges (Hunting Creek and Elk Creek) and the main Yadkin River gauge above the Cube Hydro reservoirs were used in developing regression equations of streamflow versus precipitation. The locations of these stream gauges are also provided in Figure 1. The Yadkin River gauge is regulated by reservoirs, but it was assumed that this gauge represents the total streamflow from this watershed, and also serves as a comparison to the unregulated gauges for the regression analyses. Stream gauge data were obtained in monthly mean CFS values from the U.S. Geological Survey (USGS) and converted to monthly/seasonal totals in acre-feet.

Figure 3 provides a plot of the monthly averages of the precipitation based on the eight gauges. Figure 4 provides a plot of the monthly averages of streamflow from the two unregulated tributary stream gauges (Hunting Creek and Elk Creek). A comparison of Figure 3 with Figure 4 shows that, despite precipitation reaching a peak during the summer season, streamflow at the unregulated gauges peaks in March – April, followed by a decrease to roughly half of this peak value during the summer months. This indicates significant differences between warm and cool season conversion of precipitation to streamflow. This is not due to snowpack melt since there is little snowpack accumulation in this watershed due to relatively low elevations of the watershed. The exact causes for the differences in winter and summer streamflow are unknown. Perhaps the differences may be due to seasonal evapotranspiration variations (e.g., higher evapotranspiration during the summertime).

Results from precipitation versus streamflow regression equations indicate:

- Cool season precipitation has a much higher residual runoff (e.g. greater lag time), with a significant amount of the runoff (from cool
Fig. 3. Eight station average monthly precipitation for sites shown in Figure 1, 1967-2018 (excluding any site-specific months with missing data).

Fig. 4. Average monthly streamflow (CFS) for unregulated gauges, Elk Creek and Hunting Creek. These are based on the published values for the combined period of record, dating to 1966 at Elk Creek and 1951 at Hunting Creek.
season precipitation) occurring during the spring and early summer months.

- Seeding only during the cool season is likely to produce year around increases in streamflow, with a greater overall benefit than warm season seeding.

- Overall, cool season seeding is likely to have about 1.4 times as much impact on annual streamflow as warm-season seeding (assuming the same percentage increase in precipitation), with the cool season increase more evenly distributed throughout the year.

Multiple regression equations were developed utilizing individual as well as group averages of the eight station precipitation data, relating the annual (calendar year) precipitation totals at these sites to the annual unregulated runoff (sum of Hunting Creek and Elk Creek) and the annual runoff from the main Yadkin River gauge. These equations were based on precipitation and streamflow data from 1967 to 2017.

Applications of these regression equations suggest that aircraft-based cloud seeding during the cool season using an estimated average precipitation increase of 4.1% would result in an estimated 5.2% annual increase in streamflow or 109,200 acre-feet. Other NAWC winter feasibility/design studies have shown higher estimated percentage increases in streamflow than in precipitation (e.g., Griffith, et al., 2012). One potential explanation for these differences is that evapotranspiration and ground water recharge requirements are met by the non-augmented precipitation such that increases estimated to be produced due to cloud seeding are added to the streamflow once these base requirements are met.

The 4.1% estimated seasonal increase in precipitation for this target area is somewhat lower than the range of potential increases of 5% to 15% cited in the Weather Modification Association’s Capabilities Statement on Weather Modification (WMA 2016).

4.0 PROGRAM DESIGN

Based on detailed research, analysis, and modelling, NAWC developed a proposed program design. The ASCE 2016 Guidelines recommend, “When possible the feasibility study for a program should draw significantly from previous research and well-conducted operational programs that are similar to the proposed program.” Cloud seeding programs designed to augment precipitation are uncommon east of the Mississippi River because adequate precipitation routinely falls in the Eastern United States. Consequently, the program design was based upon numerous winter research and operational programs conducted in the Western United States. The cloud physics principles that underpin cloud seeding programs to augment precipitation, however, are universal. What was not readily available for this study were any estimates of potential increases in precipitation from similar programs in the Eastern United States. The analysis in the previous section describes how NAWC made such estimates.

The design recommends using one cloud seeding aircraft during the cool season (November – April). The seeding aircraft would be a twin-engine, pressurized, turbocharged piston or turbine aircraft. Silver iodide would be the seeding agent dispensed from special seeding generators mounted on the aircraft. These generators burn a solution of silver iodide dissolved in acetone. Figure 5 provides a photo of a silver iodide generator mounted under the wing of a seeding aircraft. Aircraft seeding using silver iodide flares was estimated to be significantly more costly (approximately a factor of ten higher) than using silver iodide burners to produce continuous seeding plumes along the designated aircraft flight paths. Consideration of seeding from the ground was dismissed due to the vertical distance silver iodide particles released at ground level would need to travel to reach the -5 °C level (the threshold activation temperature of silver iodide) and the frequent presence of low-level atmospheric stable layers below this level. A premise of the analysis was that seeding flights would be conducted in both
daytime and nighttime storm periods. Unlike some programs in the mountainous west, there should be little concern about the accumulation of heavy icing on the airframe that cannot be shed by the aircraft descending to temperatures above freezing. In other words, the relatively elevated heights of the freezing level combined with rather low elevations of underlying terrain would provide adequate airspace for the shedding of ice.

The seeding aircraft would be based at a suitable airport, with possible locations being the Asheville Regional, Hickory Regional, or Wilkes County Airports. Experienced project personnel, including a project meteorologist and pilot, would be necessary to conduct operations. The project meteorologist would make operational decisions for the program. A variety of observations and computer models are available to recognize “seedable” situations and means of targeting the effects of the cloud seeding to impact the Yadkin Basin. For example, the combination of NWS NEXRAD sites at Charlotte, North Carolina; Greensville, South Carolina; Knoxville, Tennessee; and Roanoke, Virginia should provide good radar coverage of the proposed target area during “seedable” storm periods. Also, a script (developed by Idaho Power Company and subsequently provided to NAWC in 2017 in a joint effort to improve cloud seeding operations) can display various meteorological variables forecast by the High Resolution Rapid Refresh (HRRR) model, and was used to forecast the occurrence of supercooled liquid water over the Yadkin Basin during cool storm periods. Some National Weather Service websites forecast the occurrence of icing on aircraft, caused by the presence of supercooled cloud droplets at different flight levels that can also be used to predict “seedable” conditions. As an option, NAWC recommended the collection of one season of microwave radiometer observations primarily to document the frequency and magnitude of supercooled liquid water during storm periods.

The contractor selected to perform this work for Cube Hydro will develop, in consultation with Cube Hydro personnel, a comprehensive operations plan specifically for the Yadkin Basin that provides details on how the program will be conducted, including criteria that would be followed to suspend seeding operations. For example, this plan should

![Cloud seeding aircraft equipped with acetone/silver iodide solution generators, one under each wing tip.](image-url)
include a methodology of how flight tracks will be selected for each seedable storm event, taking into account upper level winds and the height of the -5 °C level. Stronger wind events would require flight paths further upwind of the target area versus lighter wind events. The selected tracks would then be used in obtaining flight clearances from the Federal Aviation Administration (FAA).

Program communications and reporting procedures were developed as part of the program design. The State of North Carolina currently does not have any regulations governing cloud seeding in the State.

5.0 ESTABLISHMENT OF OPERATIONAL CRITERIA

The on-site project meteorologist will monitor a variety of weather products available online to determine when “seedable” conditions are likely to exist over the target area. This assumes that supercooled cloud droplets are expected to occur at temperatures of -5 °C or colder for at least a few hours duration and that no seeding suspension criteria are met or forecast to occur.

The seeding aircraft would be launched following clearance of flight plans by the FAA and flown along paths specified by the project meteorologist. The flight paths will be determined primarily based upon: 1) upper-level wind directions and velocities, 2) time of nucleation then growth of ice crystals and snowflakes 3) their conversion to raindrops as they fall through the freezing level and 4) typical terminal velocities of these hydrometeors. Regarding upper-level wind information, local NWS NEXRAD doppler radar data would provide vertical plots of winds at 1,000 foot intervals throughout the radar scans that indicate the presence of clouds based upon radar reflectivity. These scans are updated approximately every six minutes. Flights would typically be conducted at the -5 °C level unless significant aircraft icing is encountered. In this situation, the seeding aircraft could be flown at the freezing level or at temperatures slightly warmer than freezing to avoid build-up of significant icing on the airframe. Areas of heavy icing (e.g. concentrated supercooled water) are generally associated with stronger upward velocity of the airmasses. This could make flying just below the freezing level a reasonable option since the silver iodide nuclei would be quickly transported to the -5 °C level. There would be frequent communications via radio between the on-site project meteorologist and the pilot during seeding missions.

The potential target area was divided roughly into four quadrants. When the northwest and southeast groups of precipitation data were inserted into the regression equations and scaled according to the average precipitation totals in these areas, results suggest that roughly two-thirds of the runoff is likely originating in the higher northwestern half of the basin. From this analysis, a descending seeding priority order when “seedable” conditions exist over the entire target area was established. In storms where “seedable” conditions exist over more than one of the four quadrant areas, the priority of seeding by area will be:

1. Northwest portion of target area.
2. Southwest portion of target area.
3. Northeast portion of target area.
4. Southeast portion of target area.

6.0 EVALUATIONS OF SEEDING EFFECTS

An historical target/control evaluation technique was developed that could be used to estimate the effects of cloud seeding in the Yadkin Basin target area following the completion of each operational season. Dennis 1980 discusses this evaluation technique. The basic approach consists of selecting an area or areas typically upwind of a designated target area. The historical data (e.g., precipitation and/or streamflow) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities. These historical data are evaluated for the same seasonal time period
as that when seeding will be conducted. The target and control sets of data for the unseeded seasons are used to develop an equation (typically a linear or a multiple linear regression equation) that predicts the amount of target area precipitation or streamflow, based on the precipitation or streamflow observed in the control area. This regression equation is then used during the seeded period, to estimate what the target area precipitation or streamflow should have been without seeding, based on the control area precipitation. NAWC had previously identified two unregulated stream gauge stations within the intended target area. These gauge locations are Hunting Creek (USGS gauge #02118500) and Elk Creek (USGS gauge #02111180). In addition, the main Yadkin River gauge (#02116500), although regulated by reservoirs, can be utilized as a target site representing essentially the total runoff from the target area. Four stream gauges were identified that could serve as control gauges. Three of these gauges were located southwest of the target area and one north of the target area. Multiple regression equations were developed for seasonal and annual time periods and for the two unregulated stream gauges (combined) and the one regulated stream gauge. For example, for the regulated Yadkin River gauge for annual streamflow (acre-feet) the multiple regression equation was: \( Y = 4.2573 \times (x1) + 0.6737 \times (x2) + 17.818 \times (x3) + 2.3747 \times (x4) + 31,481 \) where \( Y \) is the predicted streamflow and \( x1 \) through \( x4 \) are the four unregulated control gauges. The \( r^2 \) value for this equation was an acceptable 0.86.

7.0 COST AND BENEFIT/COST ESTIMATES

Cost estimates were prepared for a cool season program. Once the estimated costs were established, a benefit/cost estimate was developed. Cube Hydro provided NAWC an estimate of the value of water in the Yadkin Basin based upon hydropower production. This value was then used with the estimated cost of the program to calculate a benefit/cost ratio. The result was an estimated 5/1 ratio (the minimum ratio suggested in the American Society of Civil Engineer’s “Guidelines for Cloud Seeding to Augment Precipitation, Third Edition”, ASCE 2016) indicating that the proposed program is economically feasible.

8.0 ENVIRONMENTAL CONSIDERATIONS

Previous comprehensive environmental studies and statements on the environmental impacts of cloud seeding programs were cited (Harris 1981; BUREC 2010). Several recent Mitigated Negative Declarations (MND’s) have been prepared for winter cloud seeding programs in California following California Environmental Quality Act (CEQA) procedures (e.g., SMUD 2017). The Weather Modification Association adopted a policy in 2009 concerning the potential toxicity of silver iodide as used in cloud seeding programs (WMA 2009). These documents would suggest that no significant environmental impacts are expected from the Yadkin Basin cloud seeding program as proposed in this design study.

9.0 GENERAL LEGISLATIVE IMPLICATIONS

Currently there are no state cloud seeding regulations in North Carolina. Consequently, no permit or reporting requirements are currently needed to conduct a cloud seeding program in the state. The only required reporting for the proposed Yadkin Basin program would be to comply with a 1971 National Oceanic and Atmospheric Administration (NOAA) Public Law 92-205 that requires all non-federally sponsored attempts to modify the weather be reported to the Secretary of Commerce of the United States. Public Law 92-205 requires the submittal of Initial, Interim and final reports covering weather modification activities for individual target areas.

10.0 FINAL REPORT

NAWC prepared a comprehensive final report describing the various components of this study.
11.0 SUMMARY

The American Society of Civil Engineers (ASCE) published a recent update to an earlier publication entitled “Guidelines for Cloud Seeding to Augment Precipitation” (ASCE 2016, Third Edition). This publication contains a section on feasibility/design studies. In this publication, ASCE states, “Before a cloud seeding program is implemented, a feasibility study, as described in Section 6.3, should be conducted to assess the probability of the program being successful.” Based on ASCE 2016 criteria, the cloud seeding program designed for the Yadkin Basin is considered both technically and economically feasible as recommended in this publication. It is therefore concluded that the proposed program is feasible.

12.0 REFERENCES


