ISSN: 2634 - 8845

Journal of Earth and Environmental Science Research

SCIENTIFIC Research and Community

Research Article

Open Access

# Impact Assessment of Cloud Seeding in Karnataka, India

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## ABSTRACT
The State of Karnataka in Southern India falls in the rain shadow region and is highly prone to drought conditions. Most of the monsoon rainfall occurs in the months of June and August with few rainy days during September to December. The State experienced severe rainfall deficiency in the years of 2017 and 2019 with limited rainfall in most parts of the State. The cloud seeding exercise was taken up by the State Government in both years to mitigate the adverse impact. Two cloud seeding aircrafts (Beach Aircraft King Air 200) of Weather Modification INC, USA with meteorological instruments and cloud seeding equipment were operated. Daily advisory on convective cloud development and potential seeding locations was generated using real time data from 3 Doppler Weather radars, Radio Sonde ascents, INSAT satellite data and high-resolution model runs by India Meteorological Department and Space Applications Centre (ISRO). Real time aircraft observations of cloud temperature, liquid water content and updraft winds helped to target potential clouds for hygroscopic and glaciogenic seeding. The data from the dense rainguage network of over 6000 automatic and telemetric rainguages operated by the Karnataka State Natural Disaster Monitoring Centre was utilized to study the impact of cloud seeding operations. Evaluation of the seeding has been carried out using spatial and statistical methods. The quantitative results indicate positive impact of cloud seeding leading to 10-15 % increase in rainfall with improved geographical spread. Thus cloud seeding carried out in a controlled and systematic basis can thus emerge as a viable support to mitigate recurrent drought hit areas. This paper presents the results of the evaluation study.

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**Received:** December 20, 2025; **Accepted:** December 26, 2025; **Published:** December 31, 2025

**Keywords:** Cloud Seeding, Convection, Weather Model, Rainfall Enhancement, Spatial Analysis, Spatial and Statistical Method, Impact Assessment

## Introduction
Water resources demand is increasing with population growth. Weather modification, commonly known as cloud seeding, is emerging as a tool to enhance precipitation. Application of scientific concepts and extensive scientific experimentation has led to operational systems for cloud seeding. The earliest cloud seeding experiment was conducted in 1946 by Vincent J. Schaefer and since then seeding has been performed from aircraft, rockets, cannons, and ground generators [1]. The cloud seeding use hygroscopic and glaciogenic materials for the rain enhancements. The hygroscopic particles trigger the rainfall process and enhance efficiency of cloud in converting moisture into water drops in the warm clouds [2]. Glaciogenic seeding provides active ice nuclei leading to ice formation and growth by Bergeron process leading to rain [3]. The process of seeding to rainfall from seeded clouds takes approximately 30 to 60 minutes [3,4].

In India, cloud studies and rain enhancement experiments carried out in 2009 under the "Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) have demonstrated very positive results [5]. The results of the study indicated that the convective clouds over rain-shadow area of peninsular India are amenable for cloud seeding. During the monsoon seasons of 2017 and 2019, an operational cloud seeding program was taken up in Karnataka State to mitigate the impact of drought due to highly deficient rainfall in most part of monsoon season. The program required setting up of weather radar network, radiosonde ascents, high resolution weather model forecasts and satellite imageries for identifying potential seeding locations. The program also used the real time data from the dense network of over 6000 automated rainguages established by Karnataka State Natural Disasters Monitoring Centre (KSNDMC) to monitor rainfall during cloud seeding operations. Two cloud seeding aircrafts (Beach Aircraft King Air 200) of Weather Modification INC, USA with meteorological instruments and cloud seeding equipment were operated. The present study is a continuation of a preliminary analysis done [6].

## Materials and Methods
### Study Area and Infrastructure
During the years 2017 and 2019, the Karnataka State in southern India experienced highly deficient rainfall in the first part of monsoon season. This led the Government of Karnataka to take up cloud seeding program to enhance rainfall and mitigate the impact of drought in most parts of the State. The CAIPEEX experiments by Indian Institute of Tropical Meteorology, Pune, has shown the potential of cloud seeding especially in the rain shadow regions of India [5]. Karnataka mostly lies in the rain shadow region of western ghats and gets potential cloud cover during monsoon season. There is a strong spatial variability in rainfall from western

to eastern side of the State with western parts receiving 300 cm and more while the eastern part receives only 30-40 cms [7].

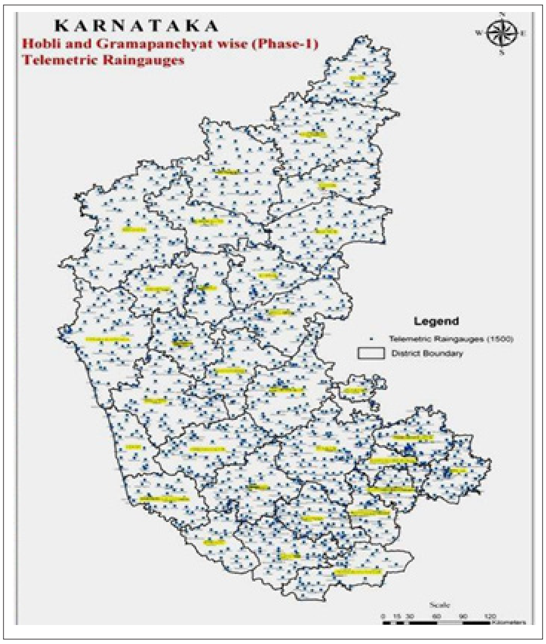
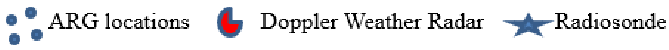



**Figure 1:** Study area with Location of Doppler Radar and Radiosonde




**Infrastructure Support for Cloud Seeding Operations**

To support the cloud seeding operations, three C- band Doppler Weather Radars were set up (Figure 1), covering almost 90% geographical area of the State. Radiosonde ascents were made on a daily basis to assess atmospheric condition. INSAT satellite imageries received through the Indian Meteorological Department (IMD) network and high-resolution weather model forecasts (3x3 km) from IMD and SAC/ ISRO were utilised. The rainfall data from over 6000 automatic rainguages (ARG) setup at Hobli level (spatial scale of 5 km2) by Karnataka State Disaster Management Centre (KSNDMC), at 15 minutes interval, was utilised for assessing the impact of cloud seeding [8]. Two pressurised aircrafts were operated by M/S Weather Modification INC, USA with hygroscopic and glaciogenic flares.

**Methodology for Identification of Seeding Areas**

The methodology followed for locating potential seeding locations on a daily basis is as shown in Figure 2. The real time weather data, satellite imageries and high-resolution model forecasts were used to identify potential zones and target cloud systems were for located using radar reflectance Z and liquid water content Wc values. Seeding operation was done based on aircraft measurements of updrafts and liquid water content in the clouds system.

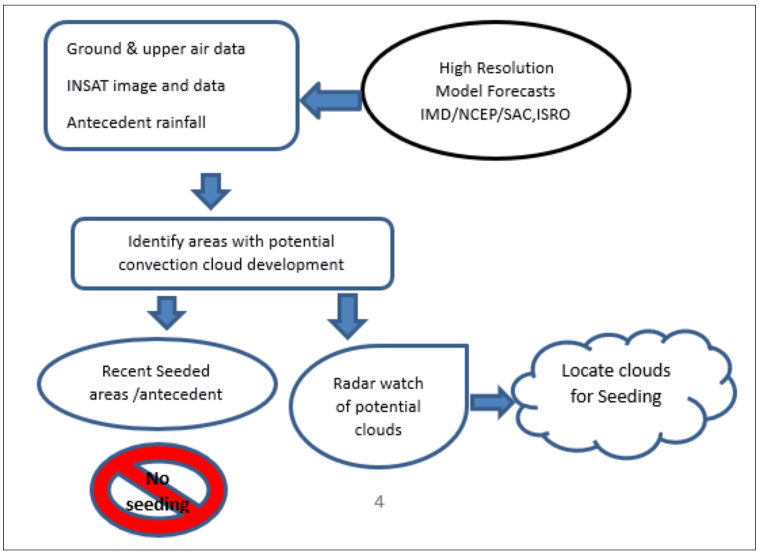



**Figure 2:** Methodology for Identification of Potential Cloud Seeding Locations

The real time inputs from the network of IMD and KSNDMC, along with the high-resolution weather model forecasts, is used for first level identification of potential areas for the day. Further, the radar observations at half hourly interval from the three locations, covering entire geographic area of the study, is analysed to detect highly convective clouds. Using the upper air data from the radiosondes giving areas with atmospheric instability conditions, specific areas for seeding are identified and an advisory is generated for aircraft operations (Figure 3).

| Date<br>District | 18 Aug. 2017 | 19 Aug. 2017 | 20 Aug. 2017 | 21 Aug. 2017 | 22 Aug. 2017 | 23 Aug. 2017 | 24 Aug. 2017 | 25 Aug. 2017 | 26 Aug. 2017 | 27 Aug. 2017 | 28 Aug. 2017 | 29 Aug. 2017 | 30 Aug. 2017 | 31 Aug. 2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bangalore Urban | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | S4 | S4 | NS |
| Bangalore Rural | NS | NS | S4 | NS | NS | NS | NS | NS | NS | S2 | S2 | S2 | S2 | S3 |
| Ramanagara | NS | NS | S4 | NS | S4 | S4 | S4 | S2 | S2 | S2 | S1 | S1 | S1 | S3 |
| Kolara | NS | NS | S3 | S3 | S1 | S1 | S1 | S2 | S2 | S2 | S2 | S2 | S2 | S3 |
| Chikballapura | S2 | NS | S2 | S3 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S2 |
| Tumkur | S2 | NS | S2 | S2 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 |
| Chitradurga | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 |
| Davangere | S1 | S1 | S1 | S2 | S2 | S2 | S2 | S1 | S1 | S1 | S1 | S1 | S1 | S3 |
| Mandya | NS | NS | S4 | S4 | S2 | S2 | S2 | S2 | S2 | S2 | S1 | S1 | S1 | S2 |
| Mysuru | NS | NS | S4 | S4 | S2 | S2 | S2 | S2 | S2 | S2 | S1 | S1 | S1 | S3 |
| Chamarajanagara | NS | NS | S3 | S4 | S3 | S3 | S3 | S2 | S1 | S1 | S1 | S1 | S1 | S2 |
| Vijayapura | S1 | S1 | S1 | S2 | S1 | S1 | S1 | S1 | S2 | S1 | S1 | S2 | S2 | S3 |
| Shivamogga | NS | NS | S4 | NS | S4 | S4 | S4 | S4 | S4 | S4 | S3 | S3 | S3 | S3 |
| Dharwad | S1 | NS | S2 | S2 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 |
| Kalburgi | S1 | NS | S3 | S2 | S1 | S1 | S1 | S2 | S2 | S3 | S3 | S4 | S4 | S4 |
| Chikmagalur | S2 | NS | S3 | NS | S3 | S3 | S3 | S3 | S2 | S3 | S2 | S2 | S2 | S3 |
| Gadag | NS | NS | S3 | S2 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 |
| Uttara Kannada | NS | NS | S3 | NS | S4 | S4 | S4 | S4 | S4 | S4 | NS | NS | NS | NS |
| Hassan | NS | NS | S3 | S4 | S2 | S2 | S2 | S2 | S1 | S1 | S1 | S1 | S1 | S2 |
| Bidar | S1 | S1 | S3 | S4 | S3 | S3 | S3 | S2 | S2 | S2 | S3 | S4 | S4 | S3 |
| Dakshina Kannada | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| Udupi | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| Bagalkote | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 |
| Haveri | S1 | NS | S3 | S3 | S2 | S2 | S2 | S1 | S1 | S1 | S1 | S1 | S1 | S1 |
| Ballari | NS | NS | S3 | S2 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 |
| Koppal | NS | NS | S3 | S2 | S1 | S1 | S1 | S! | S1 | S1 | S1 | S2 | S2 | S2 |
| Raichur | S1 | NS | S2 | S1 | S1 | S1 | S1 | S2 | S2 | S3 | S3 | NS | NS | NS |
| Kodagu | NS | NS | S3 | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| Yadgir | S1 | NS | S3 | S3 | S3 | S3 | S3 | S2 | S2 | S3 | NS | NS | NS | S3 |
| Belagavi | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 | S1 |

**Figure 3:** Typical Daily Advisory for Cloud Seeding Operations

(Note: Red Colour areas for no seeding; S1>> S2>> S3 are priority areas in decreasing order; Green colour indicates already seeded areas)

**Analysis of Cloud Seeding Data and Results**

The large amount of data from the cloud seeding operations of 2017 and 2019 in Karnataka have been analysed to quantify the impact of cloud seeding and potential cost benefit. The analysis of the data was carried out using both spatial and statistical methods. The total hours of seeding in each year was in the range of 290 hrs with as many as 750 seeding events and covering 80 % of the geographical area of the State. The seeding data consisted of precise location of seeding, time stamping, rainfall data prior and after seeding (upto 4 hrs.) from the dense network of stations, winds at upper atmosphere and radar data. The analysis consisted for spatial and statistical analysis.

In the past, evaluation of cloud seeding efficacy has been done using radar data in South Africa, Thailand and Mexico [1,2,9]. However, there are limitations in quantifying the results with radar data as the relation of radar reflectivity Z to ground rainfall R viz., R = Z b needs extensive calibration.

**Geo Spatial Rainfall Data Analysis**

The second and more direct approach is to use the rainfall data from a network of rainguage stations over the target (seeded) areas, prior and after seeding upto 4 hrs, so as to capture fully the cloud development and induced rainfall. The spatio temporal data from the dense network of telemetric rainguages (resolution 5 kms x 5 kms) at 15 minutes interval was used to determine the enhancement in rainfall due to seeding. A specially developed GIS digital database of the rainguage stations permitted mapping of rainfall over a 25 kms buffer zone around each seeding location (indicated by the symbol in the following maps). The upper air winds over the seeding locations is indicated in the maps. Studies have shown the extra area effect on cloud seeding by upper winds [10]. Figure 4 to 7 present the rainfall distribution at 5 km x 5 km resolution around the seeded areas.

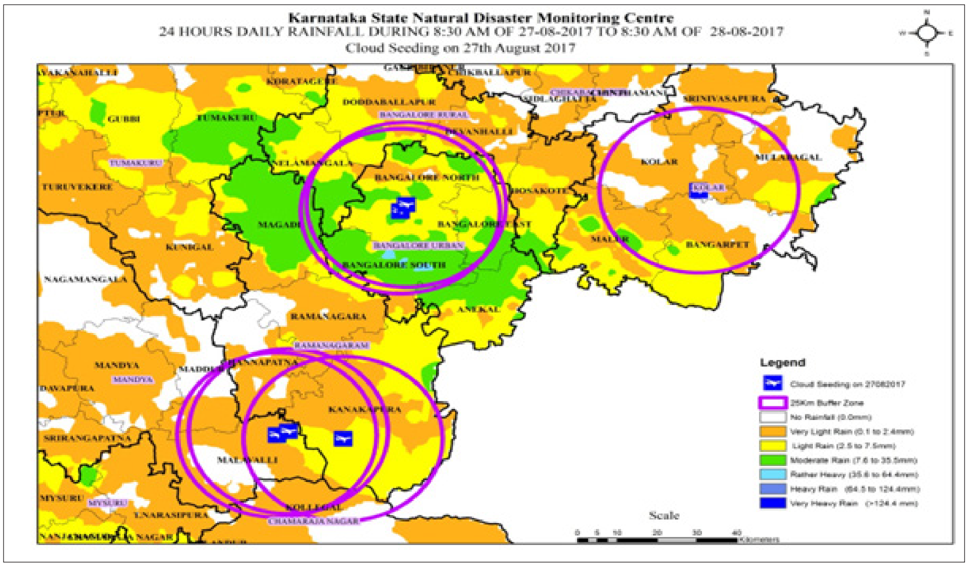



**Figure 4:** Spatial Distribution of Rainfall over 25 kms Circle Around Seeded Locations on 27 August 2017 Upper air wind flow

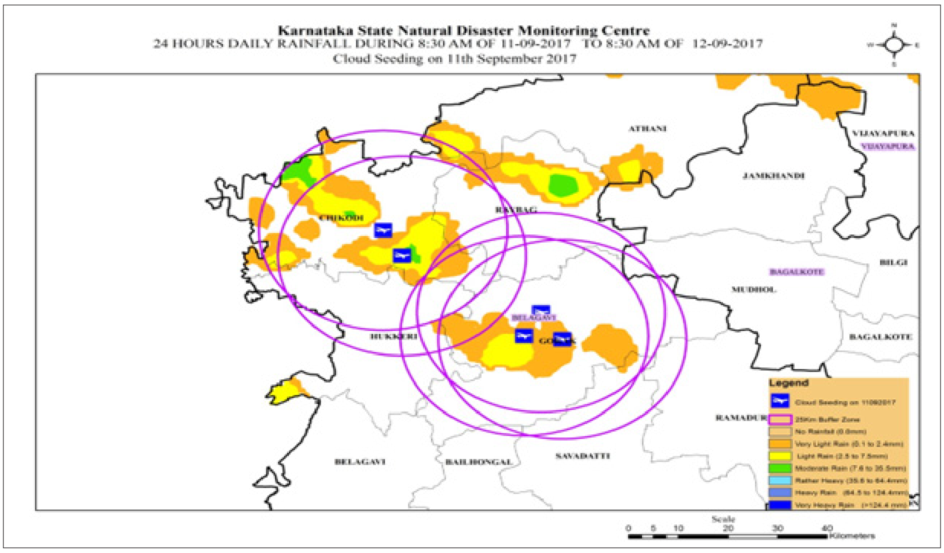



**Figure 5:** Spatial Distribution of Rainfall over 25 kms Circle Around Seeded Locations on 11 Sept. 2017, with a Typically Dry Atmosphere Upper Air Wind Flow

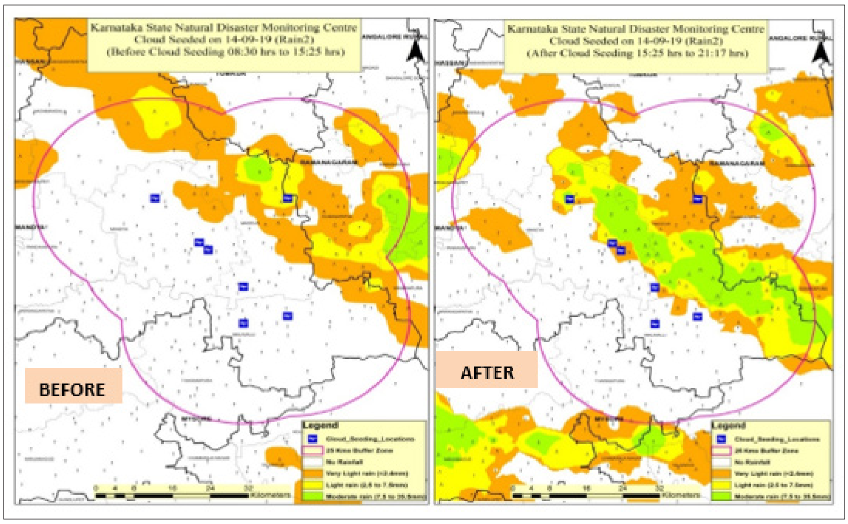



**Figure 6:** Rainfall Plot of 22 Aug. 2019 – Before and After Seeding (upto 4 hrs)

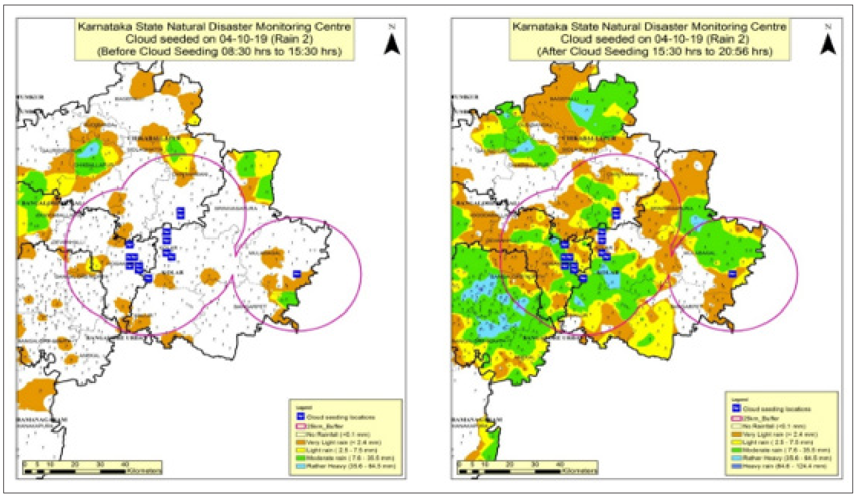



**Figure 7:** Rainfall Plot of 4 Oct.2019 – Before and After Seeding (upto 4 hrs)

The spatial plots of rainfall data from the dense rainguage network as depicted in Figure 5 to 8 have clearly brought out the initiation and spatial spread of rainfall after seeding, with the upper air winds playing a role in the direction of the spread. It is interesting to note that on one occasion, viz., 14 Sept. 2019, the post-cloud seeding maximum amount of rainfall observed in the 25kms buffer zone was as high as 33.5 mms.

**Statistical and Time series Analysis of Seeding effects**

This section deals with quantitative study of impact of seeding by statistical analysis of time series data of rainfall over the seeded locations (a buffer zone of 25 sq km.) and a time period of upto 4 hrs after seeding. The rainfall data from over 6000 stations were used for the analysis. In this method, the rainfall data from the seeded area before and after seeding (upto 4 hours) over an area of 25 sq kms buffer zone is used to develop regression relationship and quantify the seeding effect. The regression equation is computed for maximum rainfall over the buffer zone, number of stations reporting rainfall > 0.5 mm and number of stations reporting rainfall > 2.5 mm. This gives a quantitative measure of enhanced rainfall and its spatial spread.

The above data of rainfall distribution before and after seeding is graphically presented in following figures. Figure 5 and 6 show the rainfall distribution in an area of circle of radius 25 kms around the seeded areas. The impact of seeding can be seen in terms of increased rainfall (green patches) whose spatial distribution is decided by the prevailing wind condition at the cloud level. The control areas where no seeding is done show no or low rainfall.

It can be seen that there is a definite increase in maximum rainfall over the seeded locations. The increase in maximum rainfall is on the average about 15 % with few occasions showing even 60% enhancement.

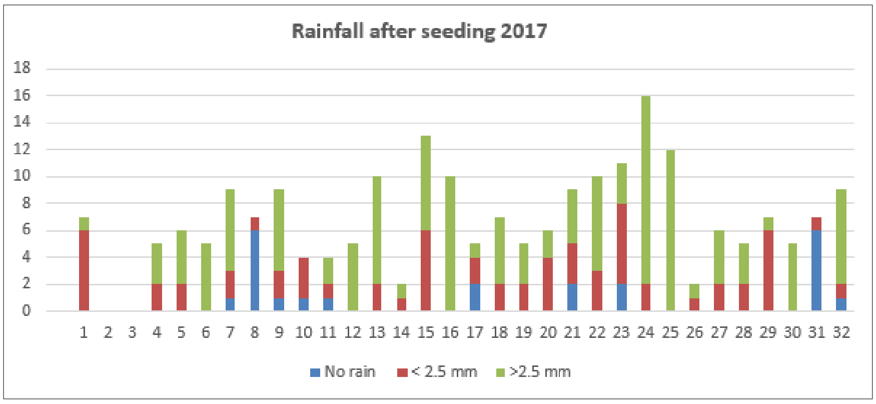



**Figure 8:** Day Wise Rainfall Plot After Seeding - Categories no Rainfall, > 0.5 mm, > 2.5 mm

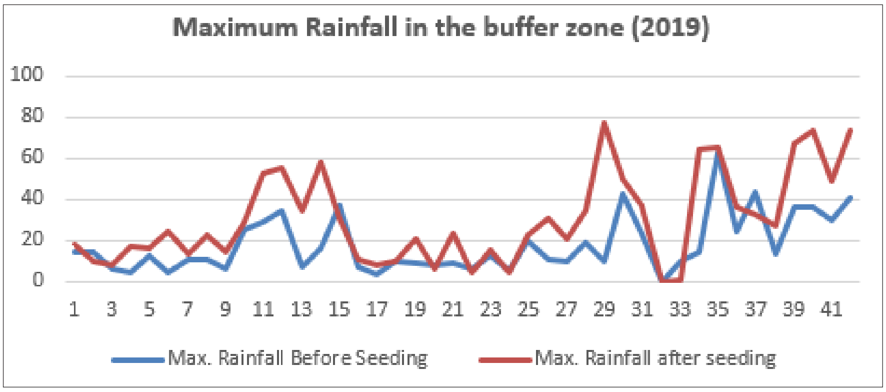



**Figure 9:** Maximum Rainfall (Before and After Seeding) in the Buffer Zone of 25 kms

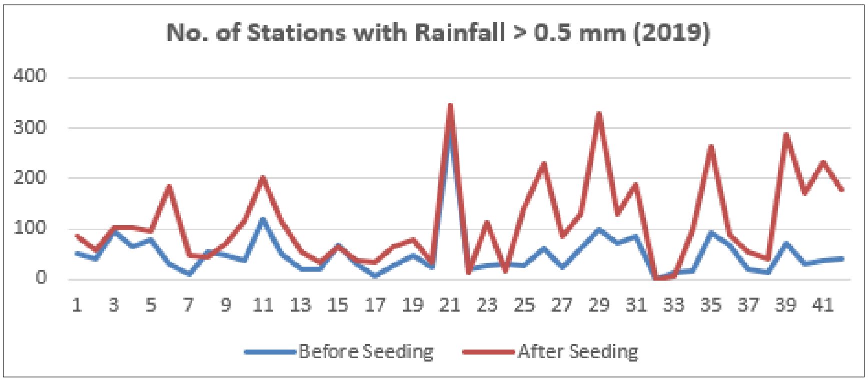



**Figure 10:** Number of Stations with Rainfall > 0.5 mm in Buffer Zone

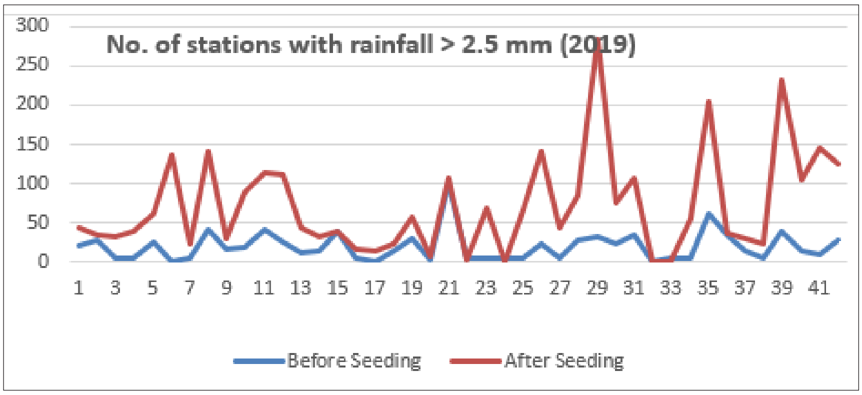



**Figure 11:** Number of Stations with Rainfall > 2.5 mm

The rainfall over the seeded locations before and after seeding is presented in Figure 9 to 11. The maximum rainfall after seeding and the number of stations in the buffer zone of 25 kms around the seeded locations with rainfall > 0.5 mm and > 2.5 mms have been plotted. The positive increase in rainfall after seeding can be seen from these figures. The impact of seeding on many occasions is in range of 10 to 20 % and on few occasions even upto 40%. On most of the occasions, the number of stations reporting enhanced rainfall covers a wide spatial distribution, indicating spread of rainfall. This has been corroborated by the spatial distribution of rainfall after seeding as seen in Figure 5 to 8. Table 1 presents the frequency of rainfall occurrence after seeding. The rainfall after seeding is mostly in the range of 20 to 40 mm. There are occasions with very heavy rainfall of 80 mm.

**Table 1: Frequency of Occurrence of Rainfall Events After Seeding**

| S.No | Maximum Rainfall range (mm) | No. of events out of 84 seeding |
|---|---|---|
| 1 | 1 to 20 | 26 (30%) |
| 2 | 21 to 40 | 45 (53%) |
| 3 | 41 to 60 | 7 (8%) |
| 4 | 61 to 80 | 6 (7%) |
| 5 | 81 to 100 | 0 |
| 6 | >101mm | 0 |
| | Total | 84 |

Table 1 presents statistical analysis of the rainfall data before and after seeding in terms of increased rainfall and spread in terms of number of reporting stations.

**Table 2: Statistical Analysis of Rainfall (Maximum, Stations with > 0.5 mm Rainfall & Stations with > 2.5 mm Rainfall) 2019**

| Parameter | No. of days of data | Correlation Coefficient | Best fit Equation (mms) |
|---|---|---|---|
| Maximum Rainfall | 42 | 0.69 | Y = 1.1 X + 10.4 |
| No. of stations with rainfall > 0.5 mm | 42 | 0.68 | Y= 1.23 X + 50.8 |
| No. of stations with rainfall >2.5 mm | 42 | 0.52 | Y= 1.72 X + 38.2 |
| **X --- prior to seeding Y --- post seeding Average increase in rainfall = 12.5 mm** | | | |

The analysis shows a positive effect of seeding in terms of increased rainfall and spatial spread. The increase ranges from 11 to 20 %. Seeding is seen to initiate rainfall over a larger area. Seen in conjunction with Table 2, it can be concluded that rainfall shows an increase in the range of > 20 mm and over an increased geographical area of 70 % compared to pre seeding.

## Conclusions

The study is based of data from cloud seeding exercise carried out in the two years viz., 2017 and 2019. The dense network of automated rainguages over the study area has made it possible to study several pre and post seeding events in different geographical locations. Statistical and spatial analysis has led to following

**Conclusions:**

- Cloud seeding has shown positive impact of rainfall, leading to enhancement in rainfall and its spatial spread;
- Mean increase in rainfall over the pre seeding rainfall is estimated to be > 20%;
- The spatial data analysis of rainfall showed a spatial spread in rainfall after cloud seeding, due to the atmospheric wind flow;
- This study has led to quantitative estimation of seeding impact and its areal spread. Preliminary estimate of the additional water generated in each year due to seeding is in the range of 25,000 million litres.

## Acknowledgments

The Authors wish to express their gratitude to Dr. J. R. Kulkarni, Sr. Scientist, IITM, Pune for very useful discussions. The authors also express their sincere thanks to Dr. S.M. Gavaskar, Scientist, KSNDMC for providing valuable data for the study.

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