

ASCE Manuals and Reports on
Engineering Practice No. 81

Second
Edition

Guidelines for Cloud Seeding *to Augment* Precipitation



This is a preview. [Click here to purchase the full publication.](#)



Guidelines for Cloud Seeding to Augment Precipitation

Second Edition

Submitted by
the Standards Committee on Atmospheric Water Management
(AWM) to the Standards Development Council (SDC) of the
Environmental and Water Resources Institute (EWRI) of the American
Society of Civil Engineers (ASCE)

Completed by
Revision of ASCE Manual No. 81 Subcommittee Editors: Conrad G.
Keyes, Jr. (Chief Editor); Co-Editors: Bruce A. Boe, George W. Bomar,
Robert R. Czys, Thomas P. DeFelice, and Don A. Griffith



Published by the American
Society of Civil Engineers



Library of Congress Cataloging-in-Publication Data

Guidelines for cloud seeding to augment precipitation.—2nd ed. / completed by . . . subcommittee editors, Conrad G. Keyes, Jr., . . . [et al.].

p. cm.—(ASCE manuals and reports on engineering practice; no. 81)

Includes bibliographical references.

ISBN 0-7844-0819-X

1. Rain-making—United States—Handbooks, manuals, etc. 2. Precipitation (Meteorology)—Modification—United States—Handbooks, manuals, etc. I. Keyes, Conrad G. II. American Society of Civil Engineers. III. Series.

QC928.7.G85 2006

551.68'76—dc22

2005029297

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia 20191
www.pubs.asce.org

Any statements expressed in these materials are those of the individual authors and do not necessarily represent the views of ASCE, which takes no responsibility for any statement made herein. No reference made in this publication to any specific method, product, process or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASCE. The materials are for general information only and do not represent a standard of ASCE, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document.

ASCE makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefore. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing this information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

ASCE and American Society of Civil Engineers—Registered in U.S. Patent and Trademark Office.

Photocopies: Authorization to photocopy material for internal or personal use under circumstances not falling within the fair use provisions of the Copyright Act is granted by ASCE to libraries and other users registered with the Copyright Clearance Center (CCC) Transactional Reporting Service, provided that the base fee of \$25.00 per article is paid directly to CCC, 222 Rosewood Drive, Danvers, MA 01923. The identification for this book is 07844-0819-X/06 \$25.00. Requests for special permission or bulk copying should be addressed to Permissions & Copyright Dept., ASCE.

Copyright © 2006 by the American Society of Civil Engineers.
All Rights Reserved.

ISBN 07844-0819-X

Manufactured in the United States of America.

MANUALS AND REPORTS ON ENGINEERING PRACTICE

(As developed by the ASCE Technical Procedures Committee, July 1930, and revised March 1935, February 1962, and April 1982)

A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to the average engineer in his everyday work, rather than the findings that may be useful only occasionally or rarely. It is not in any sense a “standard,” however; nor is it so elementary or so conclusive as to provide a “rule of thumb” for nonengineers.

Furthermore, material in this series, in distinction from a paper (which expressed only one person’s observations or opinions), is the work of a committee or group selected to assemble and express information on a specific topic. As often as practicable the committee is under the direction of one or more of the Technical Divisions and Councils, and the product evolved has been subjected to review by the Executive Committee of the Division or Council. As a step in the process of this review, proposed manuscripts are often brought before the members of the Technical Divisions and Councils for comment, which may serve as the basis for improvement. When published, each work shows the names of the committees by which it was compiled and indicates clearly the several processes through which it has passed in review, in order that its merit may be definitely understood.

In February 1962 (and revised in April 1982) the Board of Direction voted to establish:

A series entitled “Manuals and Reports on Engineering Practice,” to include the Manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such Manual or Report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with applicable discussion, in books similar to past Manuals. Numbering would be consecutive and would be a continuation of present Manual numbers. In some cases of reports of joint committees, bypassing of Journal publications may be authorized.

MANUALS AND REPORTS ON ENGINEERING PRACTICE

<i>No.</i>	<i>Title</i>	<i>No.</i>	<i>Title</i>
13	Filtering Materials for Sewage Treatment Plants	76	Design of Municipal Wastewater Treatment Plants
14	Accommodation of Utility Plant Within the Rights-of-Way of Urban Streets and Highways	77	Design and Construction of Urban Stormwater Management Systems
35	A List of Translations of Foreign Literature on Hydraulics	78	Structural Fire Protection
40	Ground Water Management	79	Steel Penstocks
41	Plastic Design in Steel: A Guide and Commentary	80	Ship Channel Design
45	Consulting Engineering: A Guide for the Engagement of Engineering Services	81	Guidelines for Cloud Seeding to Augment Precipitation
46	Pipeline Route Selection for Rural and Cross-Country Pipelines	82	Odor Control in Wastewater Treatment Plants
47	Selected Abstracts on Structural Applications of Plastics	83	Environmental Site Investigation
49	Urban Planning Guide	84	Mechanical Connections in Wood Structures
50	Planning and Design Guidelines for Small Craft Harbors	85	Quality of Ground Water
51	Survey of Current Structural Research	86	Operation and Maintenance of Ground Water Facilities
52	Guide for the Design of Steel Transmission Towers	87	Urban Runoff Quality Manual
53	Criteria for Maintenance of Multilane Highways	88	Management of Water Treatment Plant Residuals
54	Sedimentation Engineering	89	Pipeline Crossings
55	Guide to Employment Conditions for Civil Engineers	90	Guide to Structural Optimization
57	Management, Operation and Maintenance of Irrigation and Drainage Systems	91	Design of Guyed Electrical Transmission Structures
59	Computer Pricing Practices	92	Manhole Inspection and Rehabilitation
60	Gravity Sanitary Sewer Design and Construction	93	Crane Safety on Construction Sites
62	Existing Sewer Evaluation and Rehabilitation	94	Inland Navigation: Locks, Dams, and Channels
63	Structural Plastics Design Manual	95	Urban Subsurface Drainage
64	Manual on Engineering Surveying	96	Guide to Improved Earthquake Performance of Electric Power Systems
65	Construction Cost Control	97	Hydraulic Modeling: Concepts and Practice
66	Structural Plastics Selection Manual	98	Conveyance of Residuals from Water and Wastewater Treatment
67	Wind Tunnel Studies of Buildings and Structures	99	Environmental Site Characterization and Remediation Design Guidance
68	Aeration: A Wastewater Treatment Process	100	Groundwater Contamination by Organic Pollutants: Analysis and Remediation
69	Sulfide in Wastewater Collection and Treatment Systems	101	Underwater Investigations
70	Evapotranspiration and Irrigation Water Requirements	103	Guide to Hiring and Retaining Great Civil Engineers
71	Agricultural Salinity Assessment and Management	104	Recommended Practice for Fiber-Reinforced Polymer Products for Overhead Utility Line Structures
72	Design of Steel Transmission Pole Structures	105	Animal Waste Containment in Lagoons
73	Quality in the Constructed Project: A Guide for Owners, Designers, and Constructors	106	Horizontal Auger Boring Projects
74	Guidelines for Electrical Transmission Line Structural Loading	107	Ship Channel Design and Operation
		108	Pipeline Design for Installation by Horizontal Directional Drilling
		109	Biologic Nutrient Removal Operation in Wastewater Treatment Plants

CONTENTS

LIST OF TABLES	x
LIST OF FIGURES	xi
FOREWORD	xii
DEDICATION	xiv
SECTION 1—EXECUTIVE SUMMARY	1
1.1 INTRODUCTION	1
1.2 WHY SEED CLOUDS?	2
1.3 APPROACHES AND RESTRICTIONS TO SEEDING CLOUDS	3
1.4 SCIENTIFIC BASIS FOR CLOUD SEEDING	4
1.5 THE CONDUCT OF CLOUD SEEDING OPERATIONS	5
1.6 HOW TO INITIATE A CLOUD SEEDING PROJECT	7
1.7 CONCLUSIONS	7
1.8 REFERENCES	8
SECTION 2—SOCIETAL, ENVIRONMENTAL, AND ECONOMIC ASPECTS OF PRECIPITATION ENHANCEMENT BY CLOUD SEEDING	9
2.1 INTRODUCTION	9
2.2 SOCIETAL ASPECTS	9
2.2.1 Studies	10
2.2.2 The Diffusion of Innovations and Cloud Seeding	10
2.2.3 Assessing Public Attitudes	11
2.2.4 Assessing Community Dynamics	13
2.2.5 Decision Processes	15
2.2.6 Public Participation Procedures	17
2.3 ENVIRONMENTAL ASPECTS	18
2.3.1 Historical Perspective	18
2.3.2 The Concept of Cumulative Effects	21
2.3.3 Case Study—The Sierra Ecology Project	22
2.3.4 Case Study—Environmental Impact Statement for a Prototype Project	23

2.4	ECONOMIC ASPECTS	25
2.4.1	Deciding the Goal and Scale of Economic Analysis	26
2.4.2	Economic Aspects of Summer Cloud Seeding	27
2.4.2.1	High Plains	27
2.4.2.2	Midwestern United States	28
2.4.3	Economic Aspects of Winter Cloud Seeding	31
2.4.3.1	Arizona and Nevada	32
2.4.3.2	Utah	33
2.4.3.3	California	34
2.4.3.4	Colorado	34
2.5	CONCLUSIONS	36
2.6	REFERENCES	37

SECTION 3—LEGAL ASPECTS OF WEATHER

	MODIFICATION OPERATIONS	43
3.1	INTRODUCTION	43
3.2	PRE-OPERATIONAL PLANNING	44
3.2.1	Role of Regulatory Entities in the States	44
3.2.2	Weather Modification Licenses	45
3.2.2.1	A Basis for Occupational Competency	45
3.2.2.2	Initiating the Process for Obtaining a License ...	45
3.2.3	Weather Modification Permits	46
3.2.3.1	Criteria Considered during the Permit Process ..	46
3.2.3.2	Site and Time Specificity	48
3.2.3.3	Historical Overview of Permitting Controversies	49
3.2.4	Impacts of Environmental Laws and Rules	49
3.2.4.1	Adherence to Environmental Constraints	49
3.2.4.2	Considerations for Environmental Impact Statement	50
3.2.5	Contractual Agreements among Sponsors and Operators	51
3.2.5.1	Perspectives of Sponsors and Operators	51
3.2.5.2	Ethical Standards Relating to Expectations and Claims	52
3.3	CONDUCTING OPERATIONS	52
3.3.1	Operational Control	52
3.3.2	Archival of Data and Information	53
3.3.3	Reporting Procedures	53
3.4	EVALUATING OPERATIONS	54
3.4.1	Legal Liabilities for Sponsors and Operators	54
3.4.1.1	Liability Theories	55
3.4.1.2	Causation	56
3.4.1.3	Defenses	56
3.4.1.4	Indemnity and Insurance	57

3.4.2	Water Rights	57
3.4.2.1	Atmospheric Water	58
3.4.2.2	Augmented Surface Water	58
3.5	CONCLUSIONS	59
3.6	REFERENCES	59

SECTION 4—THE SCIENTIFIC BASIS 61

4.1	INTRODUCTION	61
4.2	THE NATURAL PRODUCTION OF RAIN	62
4.2.1	Formation of Cloud Condensate	62
4.2.2	Cloud Initiation and Colloidal Stability	63
4.2.3	Initiation and Evolution of Precipitation	64
4.3	CLOUD SEEDING TO AUGMENT RAINFALL	66
4.3.1	Seeding to Enhance the Warm Cloud Process (Hygroscopic Seeding)	66
4.3.2	Seeding to Enhance the Cold Cloud Process (Glaciogenic Seeding)	67
4.3.3	Seeding to Enhance Development of Individual Convective Clouds	69
4.3.4	Expansion of Glaciogenic Seeding Concepts to Larger Scales	70
4.4	THE NATURAL PRODUCTION OF SNOWFALL	71
4.4.1	Formation of Cloud Condensate	71
4.4.2	Cloud Initiation, Colloidal Stability, and Evolution of Precipitation	71
4.5	CLOUD SEEDING TO AUGMENT SNOWFALL	72
4.5.1	Snow Augmentation Methods	72
4.5.2	Expansion of Snow Augmentation Concepts to Larger Scales	73
4.6	TECHNOLOGICAL ADVANCES	74
4.7	CONCLUSIONS	76
4.8	REFERENCES	76

SECTION 5—CLOUD SEEDING MODES, INSTRUMENTATION, AND STATUS OF PRECIPITATION ENHANCEMENT TECHNOLOGY 81

5.1	INTRODUCTION	81
5.2	CLOUD SEEDING MODES	81
5.2.1	Cloud Seeding Agents	82
5.2.1.1	Homogeneous Nucleating Agents	83
5.2.1.2	Heterogeneous Cloud Seeding Agents	83
5.2.1.3	Organic Cloud Seeding Materials	86

5.2.1.4	Hygroscopic Materials	86
5.2.1.5	Other Seeding Methods and Inadvertent Weather Modification	87
5.2.2	Delivery Systems	88
5.2.2.1	Aerial Application	88
5.2.2.2	Ground Application	92
5.2.2.3	Advantages and Disadvantages of Aerial and Ground Systems	95
5.2.3	Deployment of Cloud Seeding Systems	98
5.2.3.1	Dispersion of Cloud Seeding Materials in Winter and Summer Clouds	98
5.2.3.2	Aerial Cloud Seeding Modes	99
5.2.3.3	Ground-Based Cloud Seeding Modes	100
5.2.3.4	Possible Studies Related to Proper Targeting of Seeding Materials	101
5.3	INSTRUMENTATION	103
5.3.1	Real-Time Decision Making and Monitoring Instrumentation	104
5.3.1.1	Available National Weather Service Data	104
5.3.1.2	Special Project Precipitation Gauges	106
5.3.1.3	Special Project Weather Radar	108
5.3.1.4	Special Project Rawinsondes	109
5.3.1.5	Supercooled Liquid Water Observations	111
5.3.1.6	Special Project Cloud Physics Instrumentation ..	112
5.3.1.7	Other Instrumentation and Equipment	113
5.3.2	Measurements of Potential Value in Post-project Assessments	114
5.3.2.1	Precipitation Gauge Data	116
5.3.2.2	Remote Sensor Data	116
5.3.2.3	Cloud Physics Data	117
5.3.2.4	Streamflow Data	118
5.3.2.5	Snow Course Data	118
5.3.2.6	Snow Sample Data	118
5.4	STATUS OF PRECIPITATION ENHANCEMENT TECHNOLOGY	119
5.4.1	American Society of Civil Engineers	120
5.4.2	Weather Modification Association	120
5.4.3	American Meteorological Society	122
5.4.4	World Meteorological Organization	124
5.5	CONCLUSIONS	127
5.6	REFERENCES	128

SECTION 6—HOW TO IMPLEMENT A CLOUD SEEDING PROGRAM	135
6.1 INTRODUCTION	135
6.1.1 Initial Program Assessment (Feasibility Study)	136
6.1.2 The Factors Governing Implementation	136
6.2 NEEDS AND GOALS	138
6.2.1 Origin of Need and Program Justification (Program Sponsors)	138
6.2.2 Political and/or Institutional Mechanisms	139
6.3 THE FEASIBILITY STUDY	139
6.3.1 Scientific Basis	139
6.3.2 Feasibility Study Objectives (Program Scope)	140
6.3.3 Statement of Program Expectations (Likelihood of Success)	145
6.4 PROGRAM DEFINITION	146
6.4.1 Seeding Modes and Agents (Design)	146
6.4.2 The Evaluation Plan	147
6.4.3 Quantification of Findings	152
6.5 PROGRAM CONTROL	154
6.5.1 Seeding Decisions	155
6.5.2 Data Collection and Access	156
6.5.3 Seeding Suspension Criteria	157
6.5.3.1 Warm Season Suspension Criteria	157
6.5.3.2 Cold Season Suspension Criteria	159
6.6 PROGRAM MANAGEMENT	160
6.7 REFERENCES	162
GLOSSARY	165
INDEX	177