The role atmospheric water management technologies might play in water security solutions*

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* Parts of this paper were presented at the European Geophysical Union 2023 conference and the WMA 2023 annual meeting.

Introduction

Atmospheric water management professionals apply science and engineering principles to add water to a hydrodynamic ecosystem to help ensure its security and sustainability. The addition is accomplished by using cloud seeding technologies, while respecting and avoiding damage to public health, safety and the environment. Ensuring water security and sustainability requires implementing a multi-disciplinary solution 'now' and in the future, which some believe should include cloud seeding technologies (e.g., Wehbe et al. 2023). This study conceptually explored how and why cloud seeding technologies for precipitation enhancement might be a positive component within a water security and water sustainability solution. As noted in Keyes et al. (2016), WMO (2018), and ASCE (2023) for example, cloud seeding technologies have limits to their application. Water security/sustainability solutions are also very complex and have their unknowns (e.g., WMO 2018; UN 2019; WMO 2024). This paper includes a summary of atmospheric water management technologies, their applications to water security/sustainability and then a closing remark will follow.

Atmospheric Water Management (Cloud Seeding) Technologies

Operational weather modification or cloud seeding activities have been conducted for at least seven (7) decades. These activities are scientifically designed and engineered for the purpose of positively affecting the earth's hydrologic cycle, particularly with respect to the precipitation process and can increase the precipitation above normal amounts (e.g., Orville et al. 2004; Garstang et al. 2005; French et al. 2018). Garstang et al. (2005) clarifies the operational and research viewpoints, i.e., long-term existence of cloud seeding, versus the lack of understanding of the physics of the precipitation process and human effects (e.g., DeFelice 2018) as reasons behind why the research community views cloud seeding as not effective. French et al. (2018) provide additional proof that cloud seeding technologies can be effective. Positively affecting the natural precipitation process might for example be needed to undo the negative impact(s) from natural and/or anthropogenic processes and their inadvertent effects that contribute to climate change. The limitations to their application, along with the environmental friendliness of these technologies are well documented (e.g., Keyes et al. 2016; WMA 2018; WMO 2018; ASCE 2023).

Cloud seeding activities effectively enhance or augment precipitation process efficiency with no significant, if any, negative environmental impacts compared to natural processes when implemented following a standard practice (e.g., ASCE 2023). The materials used to conduct cloud seeding are commonly silver iodide (AgI) containing ice nuclei for cold clouds and hygroscopic nuclei for warm clouds. The silver iodide molecule has been mistakenly associated with free silver ion, which causes silver toxicity. AgI does not cause silver toxicity because it does not dissociate into a free silver ion (e.g., Cooper and Jolly 1970; Howell 1977; Klein 1978; Dennis 1980; Hogstrand et al. 1996; Karen et al. 1999; Sanchez et al. 1999; Edwards et al. 2005; Stone 2006; Huggins 2009; WMA 2009; Cardno ENTRIX 2011; Fisher et al. 2016; WMA 2018).

Warm cloud seeding agents (e.g., calcium chloride or $CaCl_2$, potassium chloride or KCl, NaCl) have been used during the last three (3) decades. Very few, if any, specific environmental toxicity study results have been published. The National Acid Precipitation Assessment Program (NAPAP) (e.g., NAPAP 2005) did obtain relevant wet chemistry components in precipitation and clouds and analyzed their impact on the environment and humans. The NAPAP plus the limited use of hygroscopic materials, and the lack of negative environmental reports suggest hygroscopic seeding would not likely be environmentally toxic. However, further studies are needed and should be conducted regularly before, during and after hygroscopic cloud seeding projects.

The implementation of the standard practice for precipitation enhancement (ASCE 2023) using cloud seeding technologies has built in mechanisms that help mitigate the potential for possible environmental issues from cloud seeding through adhering to standard practices, suspension criteria under hazardous conditions (e.g., snowpack depth, avalanche, severe weather), and a regulator's permit requirement (e.g., environmental impact). Hence, there is high confidence that cloud seeding technologies can support socio-economic, nature-based solutions to water security and sustainability.

Application to Solutions corresponding to Water Security and Sustainability

In 2018, 2.3 billion people were living in water stressed areas, while 3.6 billion people faced inadequate access to water at least one month per year (WMO 2024). WMO (2024) further notes that the number of people living in water stressed areas will grow to more than 5 billion by 2050. Water sustainability is about ensuring enough water for the future while water security is about having enough water now. The capacity of a population to safeguard sustainable access to adequate quantities and acceptable quality of water is commonly divided into four (4) functional focus areas or key dimensions:

(i) Drinking water and human well-being
(ii) Economic activities and development
(iii) Ecosystems
(iv) Water-related hazards and climate change.

Each key dimension generally has governance, infrastructure, economic, societal and natural influences. The natural influences mainly encompass the atmospheric portion of the water cycle and its interface with the surface, which are significant parts of the 'Water-related hazards and climate change' and 'Ecosystems' dimensions, but also effect the other dimensions. Desalination, water system management, and education are the predominant focus of water management tied to security programs (e.g., UN 2019). Obtaining water security and its sustainability requires collaboration across the focus areas, disciplines, communities and geo-political borders. Its solution then necessitates a multi-disciplined approach. Given precipitation is the only fresh input to the water system, there should be mention or at least consideration of adding precipitation to the system when it comes to water security solutions.

Cloud Seeding to Support a Water Security and Sustainability Solution or Program

Cloud seeding technologies may be useful parts of "Ecosystem" and "Water related hazards and climate change" cross sector focal area components to water security and sustainability solutions. They are designed to add precipitation to a water system supply. The operational strategy for applying established current cloud seeding technologies at a local level, might conceivably differ from their application to increase precipitation process efficiency at a water security level, depending on the; (i) root cause of the inefficiency, (ii) complexities of the scales of motion and (iii) details of the land cover/land use (LC/LU) to atmosphere interface and nuclei-cloud interactions involved in the cloud system. Root cause examples might include air pollution or high dust loading.

A possible initial high-level strategy might use cloud seeding to:

- Support extending ecosystem surface land cover/land use coverage
- Contribute to drinking water, and Economic development
- Minimize the climate extremes to sustain and enhance ecosystem efficacy.

The 'support' in the first point refers to the addition of rainwater to sustain the life cycle of the vegetation for all land uses. The second point is primarily related to economic development, i.e., enhancing seasonal outdoor recreation, agriculture, and crops. Cloud seeding could also help reduce the need to desalinate water for example.

Reconsidering how to implement a seeding program as part of a water security/sustainability solution is conceptualized in Table 1.

Conceptually, one would need to improve or reconfigure seeding strategies, cloud seeding technologies and models, observations, and ultimately decision support tools. For example, the implementation of operations might need to be annual and repeated for decades, in contrast to the current typical seasonal approach. The LC/LU extended ecosystem area would become and remain the target area. The target area is anticipated to be non-static contrary to that in typical cloud seeding projects. The operational strategy, societal incentives, public outreach, and evaluation components will all need to be reconfigured to the larger scale necessary to meet water security and sustainability goals.

Table 1: A conceptual comparison of standard practice for precipitation enhancement projects (ASCE 2023) to its use as part of a water security and sustainability solution.

	Existing Precipitation Enhancement Projects	**Water Security/Sustainability Projects**
Area	Local/regional (catchment area, county or multiple counties, full province or state)	Regional/transnational (multiple regions, entire country, multiple countries)
Duration	Seasonal, subject to funding (monthly)	Annual, long term (decades)
Seeding Target	Rural primarily Static per project year	Rural and urban, Dynamic (evolves per project year and location)
Precipitation Type	Rain, Snow, Hail	Rain, Snow
Hail Suppression	For crop damage mitigation	Not applicable for water security and sustenance
Evaluation	Target/Control, e.g., ASCE (2023) Single discipline measurement (e.g., Precipitation amount)	Target/Control, e.g., ASCE (2023) transnational/cross border Multi-discipline measurements (e.g., precipitation amount, LC/LU, sociological, economic)
Funding	Private, commercial, local government	National government(s), UN/WMO funding

The cloud seeding operations:

(i) will be focused on precipitation enhancement (ASCE 2023),
(ii) may become daily throughout the year for decades,
(iii) will be more robust and scalable regarding societal incentives and public outreach.

There may also be a need to facilitate a more dynamic evaluation framework (including monitoring). The environmental impact, science/engineering R&D, and the supporting mitigation plans (e.g., relevant environmental changes and their impacts) may also be different.

Closing Remark

Cloud seeding is a proven, viable and cost-effective technology that will enhance precipitation and is unlikely to harm the environment. It could possibly be a useful part of an implementation plan for water security/sustainability. Further work is required to evolve the standard practice framework to effectively support this application.

Acknowledgement

Many thanks to the audiences, and especially to the two reviewers, D. O'Dowd and S Collier, who provided excellent constructive comments.

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