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Opinion

Weather Modification Technology: From Emergency Intervention to Strategic Water-Resource Management in Indonesia

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Scientific Opinion

Water security is increasingly a critical challenge associated with climate variability and change. In tropical countries such as Indonesia, the challenge is not simply a lack of rainfall, but the increasing uncertainty in its timing, intensity, and spatial distribution. A prolonged rainfall deficit can rapidly reduce reservoir storage, threaten agricultural production, and constrain hydropower generation. Under these circumstances, Weather Modification Technology (WMT) should no longer be viewed merely as an emergency response but as one component of an integrated, science-based water-resource management strategy. The Indonesian experience provides an important example. A case study conducted in the Citarum Watershed of West Java during 12 March–21 April 2021 demonstrated the potential contribution of WMT to reservoir water management during a period of declining inflow. The Citarum Cascade system—comprising Saguling, Cirata, and Ir. H. Djuanda Reservoirs—is strategically important for hydropower generation, agricultural irrigation, domestic and industrial water supply, and regional economic activities. At the beginning of the intervention, reservoir water levels were below their normal operating limits, creating concerns regarding water availability and electricity security. The fundamental principle of WMT is relatively straightforward: atmospheric water resources that would otherwise remain unavailable or precipitate outside the target catchment can, under suitable meteorological conditions, be encouraged to contribute to rainfall over a designated area. In operational practice, however, the technology is not a mechanism for "creating rain from nothing." Its effectiveness depends strongly on the existence of suitable clouds, atmospheric moisture, cloud microphysical conditions, wind fields, and the timing and location of intervention. Therefore, the scientific value of WMT lies not in controlling weather arbitrarily, but in optimizing naturally available atmospheric resources.

The Citarum case provides a useful illustration of this principle. During the 35-day WMT operation, the reported local inflow into the three cascade reservoirs reached 529.5 million m3, consisting of 269.6 million m3 at Saguling, 200.8 million m3 at Cirata, and 59.1 million m3 at the Juanda Reservoir. The evaluation method estimated additional flow by comparing observed inflow with a predefined base-flow condition derived from historical hydrological records. These numbers are important not only from a meteorological perspective but also from a water-resource management perspective. The additional flow was estimated to be equivalent to water requirements for irrigating approximately 61,284.72 ha of rice fields, corresponding to an estimated rice production potential of 367,708.33 tonnes under the assumptions used in the study. The same additional water volume was estimated to correspond to approximately 307.1 million kWh of hydropower generation across the three Citarum cascade reservoirs. Perhaps more importantly, these results demonstrate that the value of WMT should not be evaluated solely by measuring rainfall enhancement.

Its real societal value emerges through the downstream hydrological and economic consequences of additional water. In the Citarum case, the study estimated a benefit-to-cost ratio of approximately 1:15 when considering electricity production alone. When the estimated benefits for agriculture and electricity were combined, the ratio increased to approximately 1:650.

This perspective shifts how WMT should be positioned within national climate adaptation policies. Rather than treating cloud seeding as an isolated atmospheric intervention, it can be incorporated into a broader chain linking atmospheric science, hydrology, reservoir operations, agriculture, energy security, and disaster-risk reduction. Such integration is particularly relevant for Indonesia because many reservoirs serve multiple functions simultaneously. A single increase in reservoir inflow can therefore generate cascading benefits across several sectors. Nevertheless, scientific caution is essential. The reported additional inflow should not automatically be interpreted as the amount of rainfall generated exclusively by WMT. Rainfall is inherently variable, and natural atmospheric processes operate simultaneously with intervention activities. The Citarum study estimated WMT's contribution using the difference between actual flow and a statistically defined base flow. While this provides an operational assessment, stronger attribution of cause and effect would benefit from independent control areas, ensemble atmospheric modeling, radar and satellite observations, cloud microphysical measurements, and statistical attribution frameworks. This is particularly important for the future development of WMT as an international scientific discipline. The next generation of operational programs should move beyond simple before-and-after comparisons toward multi-source evidence systems. Weather radar, satellite precipitation products, numerical weather prediction, atmospheric trajectory modeling, hydrological models, and high-resolution observations can be integrated to identify when and where intervention is most likely to produce measurable hydrological benefits. Such an approach would improve both scientific credibility and operational efficiency. Another important consideration is economic evaluation. The Citarum case demonstrates that the cost of WMT can be relatively small compared with the potential value of downstream water services. The study estimated an additional raw-water value of approximately Rp10.26 per m3 based on operational costs and additional flow. However, economic evaluation should increasingly incorporate uncertainty. Future assessments should report not only a single benefit-to-cost ratio but also confidence intervals and sensitivity analyses for rainfall response, reservoir inflow, crop productivity, electricity generation, operational costs, and alternative water-management strategies.

In my view, the most important future direction for WMT is therefore not simply to conduct more cloud-seeding operations, but to make those operations more measurable, predictable, and decision-oriented. WMT should become an adaptive technology embedded within a real-time water-management framework. Decisions to initiate, continue, or terminate operations should be supported by quantitative atmospheric and hydrological thresholds rather than solely by operational experience. Indonesia has a particularly strong opportunity to develop such a framework. Its tropical atmospheric environment, extensive reservoir systems, large agricultural areas, and recurrent hydrometeorological disasters provide a natural laboratory for advancing weather modification science. The experience from the Citarum Watershed demonstrates that WMT can contribute to water security, hydropower resilience, agricultural productivity, and climate adaptation when atmospheric intervention is directly linked to measurable societal outcomes. The future of WMT should therefore be defined not by the question, "Can we make it rain?" but by a more scientifically meaningful question: "Under what atmospheric conditions can weather modification produce a measurable, attributable, and economically valuable hydrological benefit?" Answering this question requires closer integration between meteorology, cloud physics, hydrology, numerical modeling, remote sensing, and water-resource management. Weather Modification Technology should consequently be considered neither a substitute for conventional water-resource infrastructure nor a universal solution to drought. Rather, it is a complementary technological option that can enhance the flexibility and resilience of water management systems. The Citarum experience provides evidence that, when carefully designed and evaluated, WMT can generate substantial potential downstream benefits. The next challenge for the scientific community is to transform these operational successes into reproducible, transparent, and quantitatively verifiable knowledge that can support long-term climate adaptation and water security in Indonesia and other water-stressed regions of the world.

Keywords: Weather Modification Technology; cloud seeding; drought mitigation; water security; reservoir management; hydropower; climate adaptation; Indonesia