Measuring the impact and economic benefits of rainfall enhancement in multiple use water catchments

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ABSTRACT

Most regions facing or soon to face physical water scarcity are also facing increased competition for water resources between agriculture and expanding industrial and urban water needs. Other water scare regions depend heavily on groundwater systems that are being heavily mined, with extraction rates well in excess of recharge rates, most notably the Arabian Peninsula. Addressing this growing imbalance between water supplies and growing demand presents a challenge that needs to address overall water use in an integrated way. Alternative water sources and management options such as desalinisation, groundwater storage, recycling and rainfall enhancement are amongst the options to improve the balance by expanding supplies, reducing evaporative and other losses and maintaining water quality. However, the cost of developing alternative sources with capacity to deliver the physical volumes of water required will be a significant issue in the growing number of water scarce regions. Hence, low cost, easily adopted and small footprint technologies may be attractive options even though there is uncertainty as how effective they may be in a particular environment. One such alternative water technology is the Atlant rainfall enhancement system that has been recently trialled in Australia. In this paper the Atlant system is described and the results from randomised field trials in Australia are presented. The statistical methods used to identify a rainfall enhancement signal amidst the large spatial and temporal variation in natural rainfall are discussed. The 2009 trial is used as a case study to estimate the economic benefits and consider the risks and returns to an investment in the Atlant technology. Such analysis can be applied to investment decisions on rainfall enhancement technologies more generally.

1. INTRODUCTION

Physical water scarcity is said to exist where the volume of water resources is not sufficient to meet a region's demand. Economic scarcity is where a region has insufficient financial resources to invest in technologies to allow existing water resources to meet demand. Most regions facing or soon to face physical water scarcity are also facing increased competition for water resources between agriculture and expanding industrial and urban water needs. Examples include Iran, Mexico and Northern China. Other water scarce regions depend heavily on groundwater systems that are being heavily mined, with extraction rates well in excess of recharge rates, most notably the Arabian Peninsula and North Africa. Economic water scarcity is a problem throughout most of subequatorial Africa. Addressing this growing imbalance between water supplies and growing demand presents a challenge that needs to address overall water use in an integrated way. That is to meet individual competing water demands in a way that best enhances the overall pool of water resources. Alternative water sources and management options such as desalinisation, groundwater storage, recycling and rainfall enhancement are amongst the options to improve the balance by expanding supplies, reducing evaporative and other losses and maintaining water quality. However, the cost of developing alternative sources with capacity to deliver the physical volumes of water required will be a significant issue in the growing number of water scarce regions.

Atlant is a rainfall enhancement system that is low cost and appears to be capable of increasing rainfall. There have only been a limited number of trials of the Atlant system, and there is considerable uncertainty as to how effective the system is, especially in different climatic and geographic systems. However, the low cost of the technology makes an attractive investment option, and from a risk management perspective a useful part of a portfolio of strategies to address the problem of water scarcity.

In this paper the Atlant system is described and the results from randomised field trials in Australia are presented. The statistical methods used to identify a rainfall enhancement signal amidst the large spatial and temporal variation in natural rainfall are discussed. The 2009 trial is used as case study to estimate the economic benefits and consider the risks and returns to an investment in the Atlant technology.

2. THE ATLANT RAIN ENHANCEMENT MODEL

Ground-based ionisation as a means of weather modification has a long history of experimental investigation including the widespread releases of ions into sub-cloud air using corona discharges generated from extensive arrays of small diameter wires connected to a high-voltage power supply, and exposed to local winds and updrafts (Vonnegut and Moore, 1959; Vonnegut et al. 1961, 1962a, 1962b). Over the years a number of field experiments have been run using technologies derived from this technique (Moore et al. 1985; Kaufman and Ruiz-Columbié, 2005, 2009). Most recently a series of field trials of ground-based ionisation rainfall enhancement technology known as Atlant (figure 1), have been conducted in Australia (Beare et al. 2010; 2011, Chambers et al. 2012).

Several mechanisms exist by which ions might influence the microphysical processes of precipitation formation at multiple stages through the process (e.g. Harrison and Carslaw, 2003; Harrison 2000, Khain et al. 2004, Tinsley et al. 2000). Although previous studies provide a plausible "chain of events" mechanism by which ions generated by the Atlant may influence precipitation, they remain unverified observationally. Initially, negative ions are generated from a high-voltage corona discharge wire array. These ions are hypothesised to become attached to particles in the atmosphere (especially soluble particles), which later act as cloud condensation nuclei (CCN). In turn, these particles are conveyed to the higher atmosphere by wind and the electric charges on them are transferred to cloud droplets. Finally the electrostatic forces on droplet interaction aid the coalescence of the cloud droplets, resulting in enhanced raindrop growth rate and ultimately increasing rainfall downwind from the Atlant ion emitter.

Figure 1. Atlant ionisation emmitter

3. ADELAIDE CASE STUDY

3.1. Summary

Setting out and testing hypotheses regarding the physical processes that would confirm the potential for ground-based ionisation to increase precipitation is a difficult and costly exercise given the need to monitor physical and chemical processes in the atmosphere. As with chemical cloud seeding, field trials are seen as the best means of establishing the efficacy of Atlant. A number of trials have now been conducted in Australia. The trials in South Australia were conducted under the oversight of an independent scientific review panel. In addition, a benefit-cost analysis was carried out as a part of the 2009 South Australian trial. Consequently, the 2009 trial is the focus of the case study presented here.

Three trials were conducted in South Australia in the Mount Lofty Ranges outside the capital city of Adelaide, from 2008 to 2010. The trials were conducted over winter and spring, when the region receives most of its annual rainfall. Rainfall and other meteorological observations were all obtained from the Australian Bureau of Meteorology and are a part of the public record. Efforts were made to improve the experimental design and methods of statistical analysis in each successive trial. The main improvement in the experimental design between 2008 and 2009 was to change from a single site operating on a randomised schedule to a randomised cross-over design with two sites in 2009. The major statistical improvement was in the way in which the spatiotemporal correlation in gauge-level rainfall observations was accounted for in the analysis. The theory underpinning this development was completed over 2009 to 2011 and published in Chambers and Chandra (2013).

The statistical methods developed for the 2010 trial were applied to the 2009 and 2010 trial data. The estimated enhancement effect from the 2009 trial was 10.5 per cent with an estimated standard error of 5.3 per cent, significant at the 95 per cent confidence level based on a standard t-test. The estimated enhancement effect from the 2010 trial was 10.0 per cent with an estimated standard error of 6.4 per cent, significant at the 90 per cent confidence level.

3.2. Features of the experimental design

The Mount Lofty Ranges are made up of low mountains and hills orientated northeast to southwest, and two Atlant sites were situated along the first significant ridgeline closest to the South Australian coast (figure 2). They were exposed to the prevailing weather—from the south west from the Southern Ocean, to the north west from overland Central and Western Australia. Precipitation exhibits complex spatial behaviour and is related to the interaction of convective processes and underlying topography. A trial area was defined by the land area covered by two 90 km radius intersecting circles centred on the Atlants. An extensive rain gauge and weather station network is in place within this trial area, and included 282 irregularly spaced rain gauges. A target area (Atlant on) and a control area (Atlant off) were defined by a 60° downwind arc emanating from each Atlant. The orientation of this arc was dynamically defined on a daily basis, being centred on the vector defining the downwind direction of the steering wind at the Atlant site. These steering wind directions were obtained using radiosonde data (vertical wind profile), at Adelaide airport. The target areas for a westerly wind are shown in figure 2. The trial ran for 128 days from August to December 2009, during which time the two sites were operated according to a randomised, asynchronous, alternating daily schedule. From a runoff perspective, the trial area included the Adelaide urban water catchment and the Lower Lakes catchment.

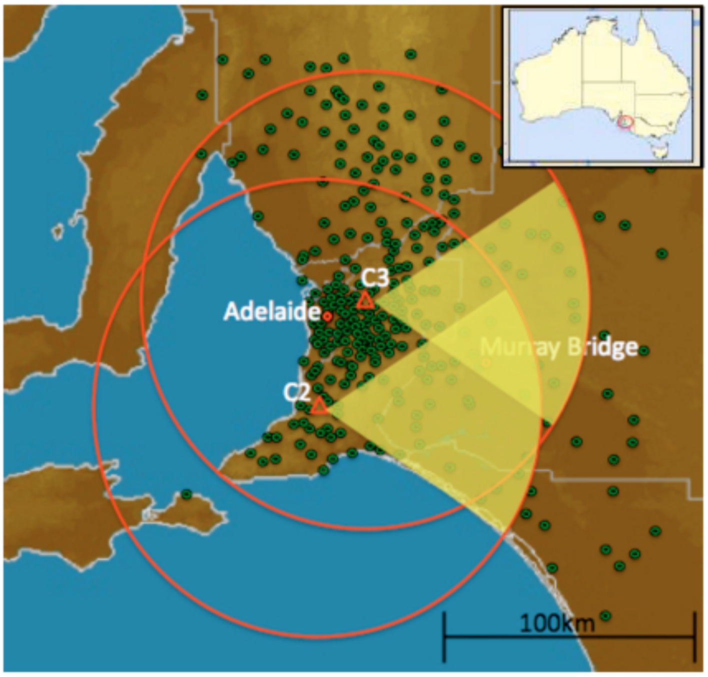

Figure 2. The location of the Atlant sites (Δ). The rain gauges used in the trial are indicated by green dots. Downwind sectors (yellow) are shown for a westerly wind.

3.3. Evaluation methodology

The analysis of rainfall enhancement trials is difficult because the aim is to detect a signal that is small relative to the natural spatial and temporal variation in rainfall. The inability to control this natural variation through the experimental design means that the power of a single trial, or even a substantial number of trials, to detect the signal with an acceptable degree of reliability is low. The first fundamental aspect of the evaluation methodology used to analyse the trial data was to develop a statistical model aimed at controlling for the expected natural level of daily rainfall at the location of individual rainfall gauge. This required estimation of the unobserved (or natural rainfall) that would have occurred in the target area had the system not been operating. The potential effect is then the difference between observed rainfall and this estimated natural rainfall. Regression modelling using covariates such as the elevation of a rain gauge, relative humidity and wind direction was used to estimate the natural rainfall.

Modelling at the individual gauge-level has advantages. In particular, when combined with gauge-level covariates these observations have information that is lost if the rainfall data are averaged to say, the daily mean level of rainfall in the target and control area. The problem is that individual gauge observations are not independent. They are correlated spatially, generally as a function of distance, and also temporally, generally as a function of the time interval. They can also be correlated both in space and time. For example, the spatial correlation between gauges tends to be greater in a downwind as opposed to a crosswind direction, as clouds tend to track downwind. Since the wind direction varies over time, this correlation changes in space and time. The implication of correlation is that the effective number of observations is less than their count. If the correlation within a day is perfect then, regardless of how many gauges there are in the trial area, there is just one observation, the mean. As the correlation falls the effective number of observations approaches the observation count. Estimation of the precision of the estimated enhancement signal therefore needs to take this correlation into account.

This is done in two ways. First, through the introduction of random effects based on the physical location of a gauge (its latitude and its longitude) and its location relative to the prevailing wind direction on a day. This latter effect was defined by tiling the downwind arc to reflect differences in the daily downwind orientation of each gauge, with a gauge then assigned to membership of a particular tile. Random effects are similar to covariates but their role is to sweep out spatial and spatiotemporal correlation between gauges that is not explained by the model covariates. Second, the standard error of the estimated enhancement effect was calculated using a semi parametric block bootstrap that resampled the data by replacing all gauge readings in each downwind tile by imputed values based on rainfall data from another, randomly selected tile from a different day. Spatio-temporal statistical models based on the correlation structure described above can be used to account for the impact of meteorological and topographic conditions not controllable by the randomised experimental design. When fitted to the data collected in 2009 these included random spatio-temporal affects that were used to account for correlations in the data due to systematic but unmeasured influences that might be inadvertently attributed to the operating status of the system.

4. ECONOMIC ANALYSIS OF THE 2009 TRIAL

The location and timing of the 2009 Adelaide trial presented a number of interesting issues in term of evaluating its benefits and costs. First, the trial area included:

- The catchment area and reservoirs that supply between 10 and 60 per cent of Adelaide fresh water, the balance coming from the River Murray
- Agricultural land supporting a variety of horticultural crops, dairy and other livestock
- A system of lakes and estuaries known as the Lower Lakes that are a listed Ramsar Convention sanctuary for migratory birds.

At the time of the trial the region had been in an extended period of drought that had seen severe water restrictions in Adelaide, which in contributed to the construction of a desalinisation plant that could supply out 50 per cent of Adelaide water supply which became operational in late 2011. In addition, throughout the Lower lakes catchment area a large decline in agricultural production and a critical decline in lake and estuary capability to support wetland ecosystems was experienced. The key point here is that additional rainfall, depending on location, has urban, productive and environmental values. The benefits of the estimated increase in rainfall attributed to the operation of the Atlant systems were calculated in three stages:

- First, the estimated contribution of the Atlant systems to total observed rainfall at each rain gauge were projected on to the catchment boundaries for urban water supplies and Lower Lake system
- Second, runoff into the urban reservoirs and the Lower Lakes that was attributed to the operation of the Atlant systems was calculated using an estimate of runoff as a proportion of total rainfall
- Third, the water was then valued in terms of opportunity cost of obtaining the water from another source.

In order to determine the amount of additional rain attributable to operation of the Atlant systems, a spatio-temporal rainfall model was used to estimate the amount of rain expected at each gauge in the trial area during the 2009 Mount Lofty Ranges trial (Beare et al., 2010). These estimates were subtracted from observed rainfall to generate values for the Atlant attribution across the 264 gauges in the trial area. These estimates varied considerably over the trial area, and can be positive or negative. A Voronoi area was then associated with each rain gauge, corresponding to the area surrounding the gauge location for which the gauge provides the physically closest observation in terms of latitude and longitude. These Voronoi gauge areas were then trimmed to the following boundaries:

- The Adelaide water catchment area (1,480 ha^2) (figure 3)
- The area of the lower lakes at full volume (2,000 ha^2) (figure 4)
- The remaining area of the Lower Lakes catchment (7,650 ha^2) (figure 4).

Volumetric enhanced rainfall enhancement attributions for each of these areas were calculated as the sum of the product of the trimmed gauge Voronoi area and the gauge-level Atlant enhancement, in mm, over the trial period; where one millimetre falling over one square kilometre is equal to one megalitre. The Atlant enhancement to rainfall in millimetres over the urban water catchment is shown in figure 3, along with the location of the Atlant systems, reservoirs and rain gauges. The Atlant enhancement to rainfall in millimetres over the Lower Lakes water catchment is shown in Figure 4.

The largest Atlant enhanced rainfall values are downwind of the winds that generally prevail over winter in the trial area (northwest to southwest). An annual runoff coefficient is the total annual runoff divided by total annual rainfall over the catchment area, indicating the proportion of runoff that occurs for a given annual rainfall in a given year. The average annual runoff coefficient for the western Mount Lofty Ranges catchment ranges is between 10 to 19.8 per cent (Heneker, 2003). Using this as a lower bound, the total additional volume of urban water supply was roughly 900 megalitres. The enhancement rainfall contribution to the Lower Lakes includes runoff and additional rain falling directly on to the lake surfaces. The latter represents an effective contribution of 100 per cent.

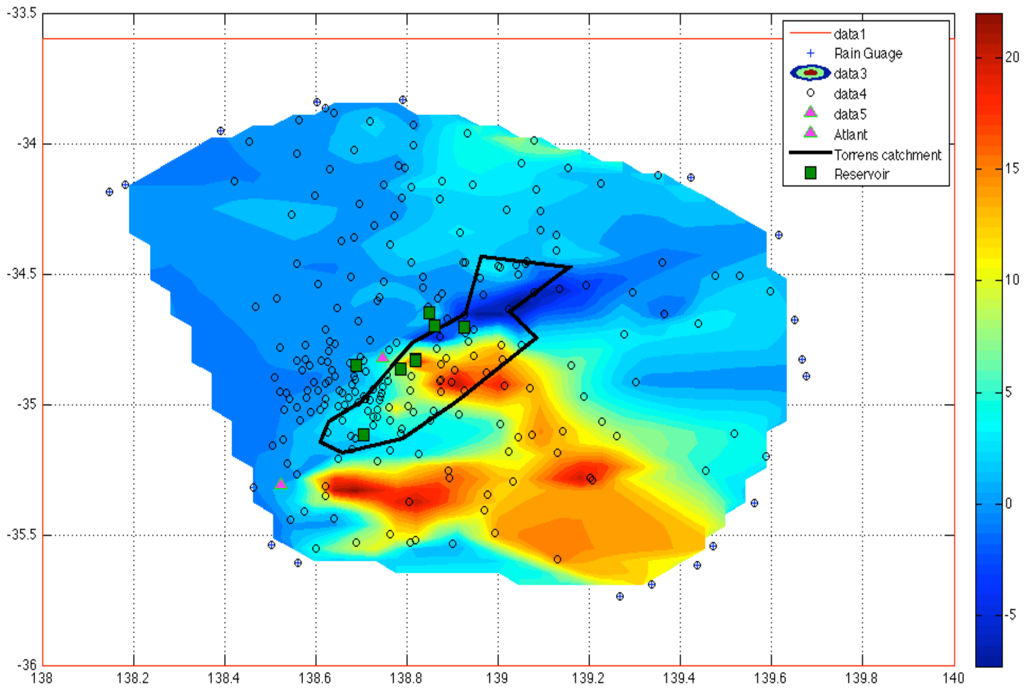

Figure 3. Estimated Atlant enhanced rain during the 2009 trial period in mm. Western Mount Lofty Ranges urban catchment marked as black outline, rain gauges as open circles.

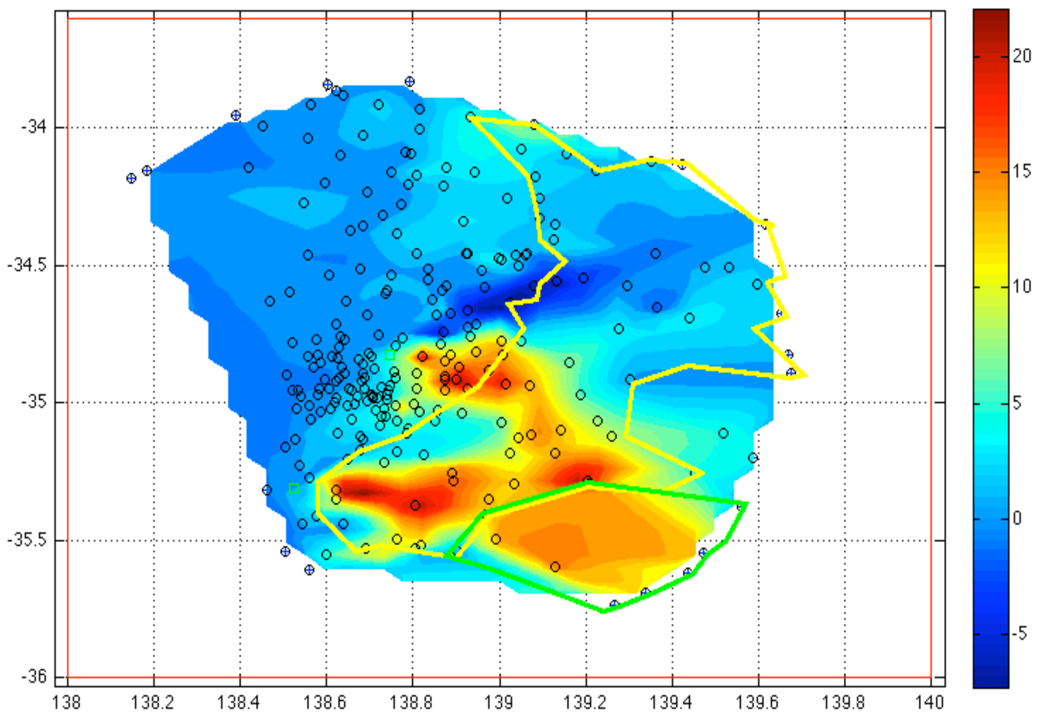

Figure 4. Estimated Atlant enhanced rain in Lower Lakes catchment (Yellow outline) area during 2009 trial period in mm. Green outline shows the Lower Lakes. Rain gauges as open circles

The National Water Commission (2005) reports an average runoff coefficient across the Lower Lakes catchment of six per cent. This was applied to rainfall that fell over land in the Lower Lakes catchment area. The total volume of additional water reaching the Lower Lakes attributable to the operation of the Atlant during the trial period was almost 26,000 megalitres. The value of the additional water for the Adelaide metropolitan area is based on the avoided operating cost of desalination of $1 per kilolitre (Brennan 2008). The additional 1,600 megalitres generated in this area by the trial has an estimated value of $1.6 million.

Additional water in Lower Lakes was valued at the cost of irrigation water. The Commonwealth of Australia has bought back irrigation water entitlements with an average yield of almost one million megalitres for environmental purposes. The prices paid to date by the Commonwealth for irrigation entitlements vary between regions and according to reliability. The weighted average expenditure in the southern connected Murray for water delivered to the environment at that time was $2,019 per megalitre. The entitlements are perpetual, so an annual cost at a discount rate of five per cent was assumed, giving an amortised value of $101 per megalitre per year. Applying this value to the additional 26,000 megalitres of water estimated for the Lower Lakes during the 2009 trial is estimated to be $2.6 million. While some benefits of additional rainfall would also accrue to agriculture in the trial region, the variety of such enterprises, irrigated and rain fed, in the region was too complex to allow explicit modelling. These were therefore not taken into explicit consideration.

A total gross benefit of $4.2 million for the trial period was estimated. A large proportion of the costs of the trial were in setting up the infrastructure as well as in data processing and analysis. A rough estimate of the annualised cost of operating the two Atlant systems is around $800,000. This would give a benefit cost ratio of almost five to one. However, there is large amount of uncertainty associated with the attribution of enhanced rainfall to the operation of the Atlant systems.

The overall estimated enhancement effects were 10.5 per cent on average gauge basis and 5.6 per cent on a Voronoi area weighted gauge basis. The area-weighted estimates, which more closely correspond to the volume of additional rain that fell in any particular area, is significant at the 80 per cent confidence level (Beare and Chambers, 2010). The break-even level of enhancement (calculated on the basis of a benefit cost ratio equal to one) is slightly greater than one per cent on a weighted area basis. This implies that there is over a 75 per cent probability that benefits of increased rainfall are greater that the cost of the technology[1]. So while there is a large degree of uncertainty about the estimated enhancement effect, the size of the expected benefits over costs is sufficient to strongly favour an investment in the technology.

5. CONCLUSIONS FROM THE TRIAL ANALYSIS

A series of trials of a rainfall enhancement technology known as Atlant were conducted in Australia in 2008 to 2010, reporting positive results. The overall estimated enhancement effects in the 2009 trial were 10.5 per cent on average gauge basis and 5.6 per cent on a Voronoi area weighted gauge basis. Based on these estimates, a total gross benefit of $4.2 million for the trial period was calculated. Using a rough estimate of the annualised cost of operating the two Atlant systems of around $800,000, yielded a benefit cost ratio of almost five to one. However, there is large amount of uncertainty associated with the attribution of enhanced rainfall to the operation of the Atlant systems.

The area-weighted rainfall enhancement estimate which more closely correspond to the volume of additional rain that fell in any particular area, is significant at the 80 per cent confidence level, and the break-even level of enhancement is slightly greater than one per cent on a weighted area basis. This implies that there is over a 75 per cent probability that benefits of increased rainfall are greater than the cost of the technology. So while there is a large degree of uncertainty about the estimated enhancement effect, the size of the expected benefits over costs is sufficient to strongly favour an investment in the technology.

The statistical techniques that have been briefly discussed here are fully documented and be useful in other water management application such evaluating chemical cloud seeding and detecting the impact of localised climate change. The economic analysis also provides a simple opportunity cost framework for comparing alternative water investments with potentially multiple benefits.

[1] This confidence intervals were calculated non parametrically, here a students t distribution is used to approximate the standard error of the estimated enhancement effect and the probability that it exceeds the break-event level.

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