Evaluation of Evaporation Suppression Tests on Lake Arrowhead, Texas

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Key Points

- During the summer of 2014 Wichita Falls responded to declining reservoir levels by implementing several strategies to extend its water supplies, including attempts to reduce evaporation losses by application of an evaporation suppressant on Lake Arrowhead.
- During a span of ten weeks from July 23, 2014, through October 2, 2014, the city of Wichita Falls applied an evaporation suppressant on Lake Arrowhead.
- We analyzed both historical and recent reservoir and meteorological data to determine the effectiveness of the suppressant in reducing evaporation from Lake Arrowhead.
- Our analysis suggests that, with an 87 percent statistical level of confidence, the suppressant reduced evaporation.
- Our analysis also suggests that the suppressant was effective in reducing evaporation by about 15 percent, although statistically there is about a 74 percent probability that the reduction lies between 0 percent and 26 percent.
- Although the data suggests that the suppressant was effective, we are unable to state this with a higher level of confidence because of the small amount of useable data. The level of confidence could be improved if additional data were collected in the future.
- This study did not consider the influence of evaporation suppression on water supply nor the economic costs and benefits of evaporation suppression. These analyses are needed prior to fully considering evaporation suppression as a water supply strategy.

Introduction

As of early November 2014, water stored in three reservoirs that supply water to the city of Wichita Falls, Lake Arrowhead, Lake Kickapoo, and Lake Kemp, had fallen to 19 percent, 26 percent, and 26 percent of conservation capacity, respectively. Continued decline, and the potential complete loss of water in these reservoirs, threatens the city's water supply. In response to low reservoir levels and in an attempt to extend its water supplies, the city applied an evaporation suppressant on Lake Arrowhead for nearly ten weeks from July 23, 2014, to October 2, 2014. This analysis attempts to evaluate the effectiveness of the suppressant in reducing evaporative losses from Lake Arrowhead.

Evaporation Suppression with Monolayers

Certain chemicals when released on a water surface will spread spontaneously into a very thin film that can act to reduce evaporation. Commonly tested chemicals for reducing evaporation include long chain fatty alcohols and acids such as cetyl alcohol, stearyl alcohol, and palmitic acid (these are also known as octadecanol, hexadecanol, and hexadecanoic acid, respectively). Cetyl alcohol was first isolated from whale oil; stearyl alcohol is produced from stearic acid which is found in many animal and vegetable fats and oils; and palmitic acid is found in palm trees, meats, and dairy products. All take the form of a white solid or flakes at room temperature and are used in the cosmetic industry in shampoos, skin creams, and lotions.

Applications of Evaporation Suppressants and Their Effectiveness

Evaporation suppressants have been shown to be effective in the laboratory and at small scales such as on swimming pools, ponds, and small lakes. Commercial vendors claim reductions in evaporation from 35 percent (Flexible Solutions 2010) to 75 percent (PRWeb 2010) for small bodies of water such as these, although it is not clear under what conditions or time frames these reductions were achieved.

La Mer (1962) provides an excellent summary of monolayers and their use to suppress evaporation. This collection of papers presented at the American Chemical Society Annual Meeting in September 1960 describes technical issues associated with monolayers, laboratory tests of the technology, and several field tests conducted in the late 1950s. Field tests were conducted on larger bodies of water in Australia, Africa, and several states in the United States including Colorado, Arizona, Oklahoma, Illinois, and Texas. Researchers in some of these studies conducted tests to evaluate the spreading and coverage efficiencies of evaporation suppressants and in other studies attempted to evaluate the effectiveness of the suppressants in reducing evaporation. The reservoirs ranged in size from as small as 2.8 acres (Illinois Department of Conservation Fish Hatchery, central Illinois) to as large as 40,000 acres (Boulder Basin of Lake Mead). The studies reported a wide range of effectiveness in reducing evaporation, ranging from about 9 percent in Lake Hefner, Oklahoma, to up to 63 percent for a 50-acre reservoir near Eagle Pass, Texas. The Texas results were based on a short period of only 10 hours and were considered ideal and similar to results for controlled tests under favorable conditions for the suppressant used, octadecanol.

The above studies reported wind to be a common issue in reducing the effectiveness of suppressants for nearly all the field tests at larger scales. Wind can move the suppressant to one side of a reservoir, reducing the spatial coverage and overall effectiveness of the suppressant. Evaluating the effectiveness of suppressants in the field presents a second challenge due to the difficulty in obtaining accurate measurements of all the factors required to complete a water budget for a reservoir.

Approach to Evaluating the Effectiveness of the Evaporation Suppressant

We tried two approaches for evaluating the effectiveness of the evaporation suppressant on Lake Arrowhead. The first approach was to compute a water budget for Lake Arrowhead alone based on measurements or estimates of (1) precipitation on the reservoir, (2) evaporation, (3) inflows, (4) withdrawals, and (5) seepage. In principle this approach would allow one to differentiate evaporation rates that occur when the suppressant is applied from rates when it is not applied, and thus would allow one to evaluate the effectiveness of the suppressant. However, this approach was problematic primarily because the water budget did not balance well enough to detect the small changes in evaporation that were expected due to application of the suppressant. Changes in evaporation due to the suppressant were lost in the noise mainly due to uncertainty in estimates of rainfall and inflow when rainfall occurs and due to uncertainties in estimating lake evaporation. This approach to evaluating the effectiveness of evaporation suppressants would likely not work in the future without significant improvements in determining inflows, rainfall on the reservoir, and evaporation from the reservoir.

An alternate approach we used in this study considers Lake Kickapoo evaporation as a reference for comparison to Lake Arrowhead evaporation. Because of their proximity to each other (being only about 25 miles apart) and because they experience similar meteorology, we assumed that evaporation from both reservoirs would be similar. We were also able to reduce noise in the data significantly by considering only days when rainfall and inflows are small or zero and only when reservoir levels in both lakes are declining. We computed evaporation for both lakes based on lake levels and withdrawals and then computed the ratio of evaporation from Lake Arrowhead to that for Lake Kickapoo. Finally, we compared the evaporation ratios for the period prior to application of the suppressant and during the application of the suppressant by applying a Student's t-test. We provide additional details of this approach in Appendix A.

Background Conditions

During the testing period from July 23, 2014, to October 2, 2014, daily average elevations in Lake Arrowhead declined by 1.08 feet from 907.68 feet to 906.60 feet. During the same period storage declined from 51,040 acre-feet to 45,015 acre-feet while the surface area decreased from 5,753 acres to 5,373 acres. Lake Kickapoo elevations declined 1.48 feet from 1,031.40 feet to 1,029.92 feet during the testing period. Storage in Lake Kickapoo declined from 27,759 acre-feet to 23,787 acre-feet, and surface area fell from 2,796 acres to 2,562 acres.

Both lakes lie within Quadrangle 409 in Texas (TWDB 2014) and experience similar evaporation and precipitation rates. Historical average lake gross evaporation for this area of the state for July, August, September, and October declines from 8.73 inches in July to 4.97 inches in October (TWDB 2014). Evaporation for a given month is variable from year to year. For example, observed July evaporation ranges from 5.48 inches to 12.82 inches, and October evaporation ranges from 4.97 inches to 7.18 inches (Table 1). Precipitation in July, August, September, and October averages 2.07 inches, 2.20 inches, 3.24 inches, and 3.12 inches, respectively. Precipitation for a given month is also highly variable (Table 2) from year to year.

Table 1. Historical (1954 to 2013) gross lake evaporation for Quadrangle 409 in Texas, representing Lake Arrowhead and Lake Kickapoo.

Month	Average (inches)	Minimum (inches)	Maximum (inches)
July	8.73	5.48	12.82
August	8.15	5.09	13.35
September	6.11	3.16	9.10
October	4.97	2.20	7.18

Table 2. Historical (1954 to 2013) precipitation for Quadrangle 409 in Texas, representing Lake Arrowhead and Lake Kickapoo.

Month	Average (inches)	Minimum (inches)	Maximum (inches)
July	2.07	0.01	8.32
August	2.20	0.00	7.42
September	3.24	0.19	8.95
October	3.12	0.00	12.47

Application of Evaporation Suppressant to Lake Arrowhead

The City of Wichita Falls applied WaterSavr™, a commercially available evaporation suppressant, to Lake Arrowhead during these tests (references to brand names in this report does not imply endorsement by the Texas Water Development Board or staff). WaterSavr™ is a patented mix of hydrated lime powder with food grade stearyl and cetyl alcohols (Flexible Solutions 2014). It spreads spontaneously on water to form a monomolecular layer to inhibit evaporation.

The suppressant was distributed by boat at various locations in the reservoir. The suppressant was applied from July 23, 2014, through October 2, 2014, typically by applying two days in a row and then skipping application for one or two days. Reapplication is needed because the suppressant biodegrades over the span of a few days and because on windy days it is blown to the edge of the reservoir, rendering it ineffective.

Results

Following the approach described above, we determined that changes in elevation due primarily to evaporation alone were similar in both lakes in earlier years when no suppressant was applied and that the suppressant was effective in altering the elevation changes of Lake Arrowhead relative to those of Lake Kickapoo. Results of the analysis suggest that, with an 87 percent statistical level of confidence, the suppressant was effective in reducing evaporation. Although we were not able to reach this conclusion at a higher level of confidence because of the small data set available, the data suggests that the evaporation suppression did reduce evaporation from Lake Arrowhead. Our analysis also suggests that the suppressant was effective in reducing evaporation by about 15 percent, although statistically there is about a 74 percent probability that the reduction lies between 0 percent and 26 percent.

This study was focused on estimating how much of an impact the suppressant had on evaporation from the reservoir. We did not do an analysis of the influence of evaporation suppression on water supply nor the economic costs and benefits of evaporation suppression. These analyses are needed, presumably on a case-by-case basis, prior to fully considering evaporation suppression as a water supply strategy.

Reducing Uncertainty in Results

Uncertainty in the results arises from the small amount of data that was available for the analysis. We deemed only 10 data points of historical data and 4 data points of recent data, during which the suppressant was applied, of sufficient quality to be used in our analysis. An increase in the number of data points collected while the suppressant was applied would help to increase confidence in the results. A repeat of the application of the suppressant in the future during the June to September time frame, as in the current study, would help provide additional data. As in the current analysis, lake levels for both lakes and daily diversion data would also be needed. Also, as in the current analysis, only periods during which inflows to the lakes and rainfall on the lakes were small or zero would be used in the analysis, so a repeat of the study during low-rainfall and low-flow conditions would be required.

References

La Mer, V., 1962, Retardation of Evaporation by Monolayers: Transport Processes. Academic Press, New York and London, 277 p.

Texas Water Development Board, 2014, http://www.twdb.state.tx.us/surfacewater/conditions/evaporation/index.asp, Quadrangle 409, accessed December 10, 2014.

PRWeb, 2010, http://www.prweb.com/releases/2010/12/prweb8031677.htm, accessed December 10, 2014.

Flexible Solutions, 2014, http://www.flexiblesolutions.com/products/watersavr/default.shtml, accessed December 10, 2014.

Appendix A

This analysis was based on a comparison of evaporation from Lake Arrowhead and Lake Kickapoo during two time periods. The first data set is composed of data collected in 2012 and 2013 prior to application of evaporation suppressant to Lake Arrowhead. This data set is the control group and will be referred to as the **Prior** data set in the remainder of this appendix. The second data set is composed of data collected in July to October 2014 at a time when evaporation suppressant was applied to Lake Arrowhead. This data set will be referred to as the **During** data set in the remainder of this appendix. The analysis attempts to identify changes in the ratio between evaporation from Lakes Arrowhead and Kickapoo prior to and during the application of the suppressant.

We used a mass balance to calculate evaporation from both lakes. To carry out those calculations, we estimated the volume of each lake for each day. Volumes were estimated using the average elevation for the lake for the particular day (as reported by U.S. Geological Survey Gage 07314800 Lake Arrowhead near Henrietta and U.S. Geological Survey Gage 07314000 Lake Kickapoo near Archer City) and interpolating the associated volume from the most recent elevation-area-capacity table. TWDB staff surveyed both lakes in 2013. We used the 2013 elevation-area-capacity tables for both lakes for all volume estimates, including 2012 data, in order to maintain consistent elevation-area-capacity relationships for all the data. We used the following mass balance formula to evaluate changes in volume from day i to day i+1 for each lake:

$$Volume_{i+1} = Volume_i + Inflow_i - Diversion_i + Precipitation_i - Evaporation_i - Seepage$$

We assumed seepage to be small and therefore ignored it. The City of Wichita Falls provided diversion data (either weekly or daily data). Precipitation can vary significantly across each lake and between lakes and is difficult to measure accurately. Therefore, we selected days when precipitation was zero or near zero in order to allow removal of this term. We looked at National Weather Service radar data for each date in order to identify days with zero or near zero precipitation within the watersheds of the two lakes.

Inflows to each lake are also difficult to estimate and may vary considerably from Lake Arrowhead to Lake Kickapoo. Only one tributary to Lake Arrowhead is gaged, U.S. Geological Survey Gage 07314500 Little Wichita River near Archer City. This gage has an upstream watershed area of 481 square miles, 59 percent of the total watershed area of Lake Arrowhead (822 square miles). There are no gages upstream of Lake Kickapoo, which has a contributing area of 275 square miles. Ungaged tributaries above Lake Kickapoo include Godwin, Brier, and Kickapoo creeks. Ungaged tributaries above Lake Arrowhead include Bluff, Deer, Onion, West Little Post Oak, and East Little Post Oak creeks.

Table A1. U.S. Geological Survey gages and characteristics.

Gage Number	Description	Type of Gage	Drainage Area[$mile^2$]	Period of Record
07314000	Lake Kickapoo near Archer City, TX	Lake Elevation	275	1946 to present
07314500	Little Wichita River near Archer City, TX	Stream	481	1932 to present
07314800	Lake Arrowhead near Henrietta, TX	Lake Elevation	822	1967 to present

To get around the difficulty of estimating inflow to the lakes, we calculated evaporation only for days when average daily inflow was below 5 cubic feet per second based on U.S. Geological Survey Gage 07314500. For these days, we assumed inflows (both gaged and ungagged) would be only a small percentage of diversions or evaporation and could therefore be ignored.

We made another check related to inflow and precipitation based on changes in lake elevations. We considered days when lake elevation did not decrease from the previous day to be days when inflows or precipitation had occurred and therefore eliminated such days from the calculations. Based on this parsing of the data, it was possible to consider Inflow, Precipitation, and Seepage to be zero or near zero. The mass balance equation for suitable dates becomes:

$$\text{Volume}_{i+1} = \text{Volume}_i – \text{Diversion}_i – \text{Evaporation}_i$$

Rearranging terms,

$$\text{Evaporation}_i = \text{Volume}_i - \text{Volume}_{i+1} – \text{Diversion}_i$$

In this equation, Evaporation has units of volume. We converted evaporation to units of depth by dividing by the area of the lake (interpolated from the most recent elevation-area-capacity table using the average of the elevations for the two days).

Step 1. Assemble Lake Arrowhead and Lake Kickapoo evaporation data prior to application of suppressant

The City of Wichita Falls provided diversion data for Lake Arrowhead and Lake Kickapoo for the time period June 2012 through July 2014 in weekly time steps. We divided weekly diversion data by seven in order to estimate daily diversions. However, based on daily data obtained in 2014, diversions throughout the week are not uniform. Therefore, we do not believe evaporation rates for individual days are accurate; however, estimates for the entire seven-day period should be accurate. We parsed the Lake Arrowhead and Lake Kickapoo data to find weekly periods within the months of June, July, August, or September when (1) elevations for both lakes were decreasing from day to day, (2) there was little to no precipitation in the upstream drainage areas of each lake, and (3) flow at U.S. Geological Survey gage 07314500 was less than 5 cubic feet per second (Figures A1 and A2; Appendix B includes sample calculations for evaporation). There are 10 available data points with suitable characteristics, 6 from 2012 and 4 from 2013 (Table A2).

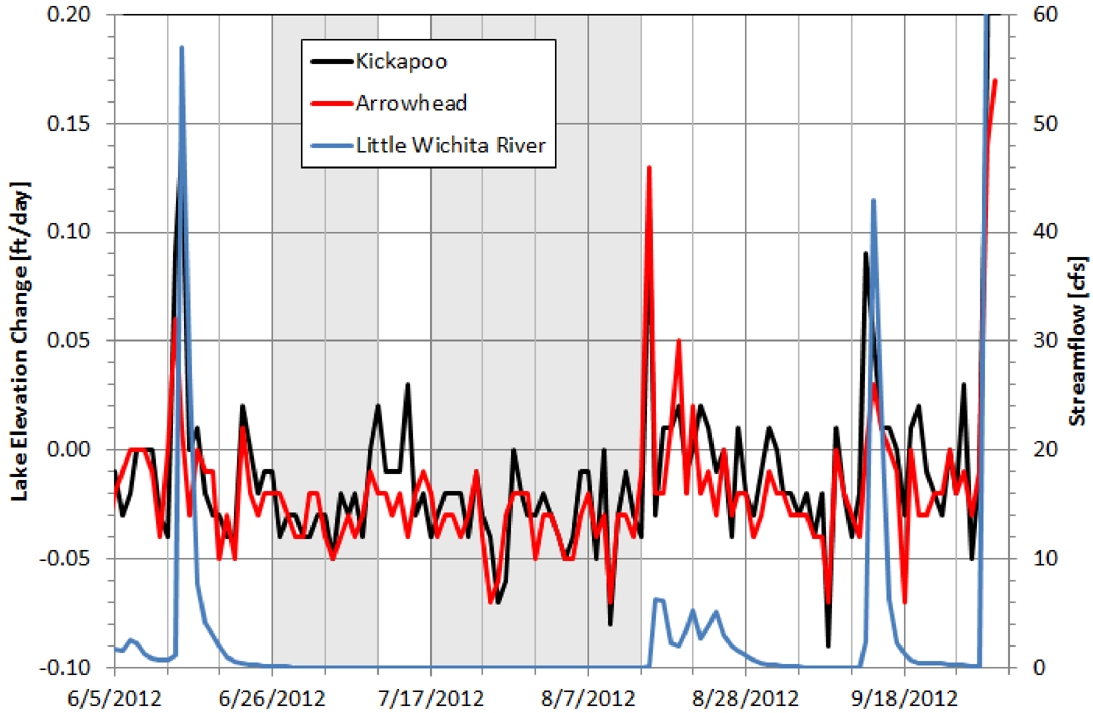

Figure A1. Daily change in lake elevation and streamflow of Little Wichita River June through September 2012. Suitable time periods for lake evaporation calculation are highlighted. (ft = feet; cfs = cubic feet per second)

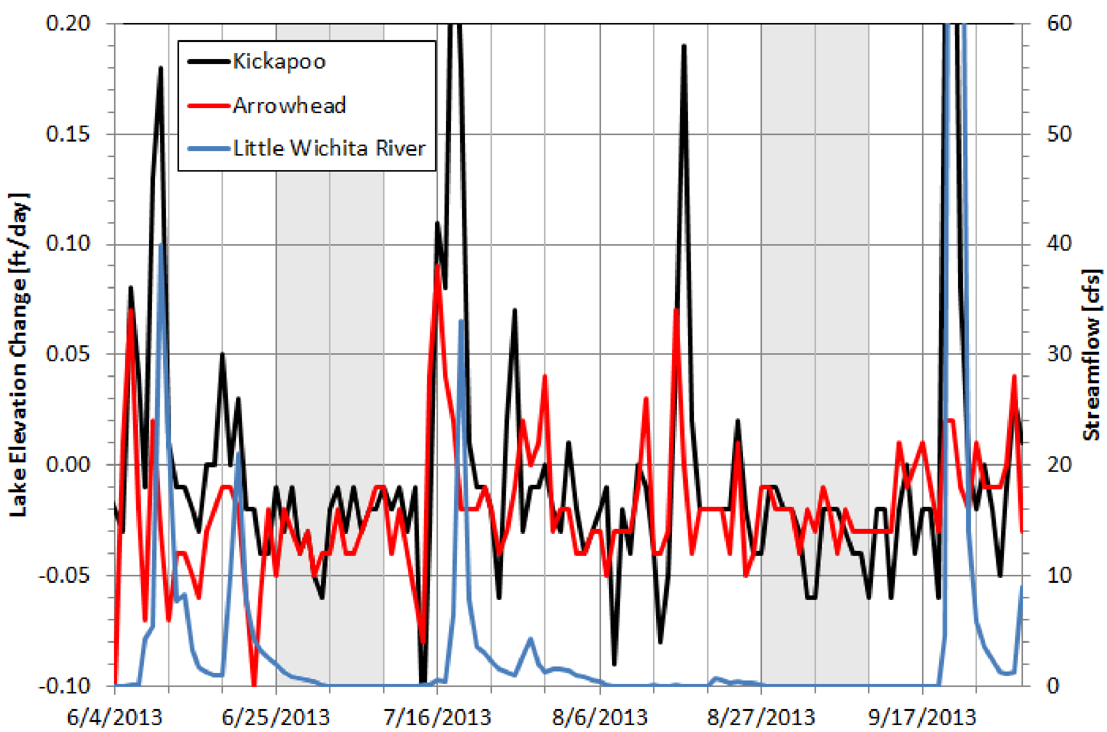

Figure A2. Daily change in lake elevation and streamflow of Little Wichita River June through September 2013. Suitable time periods for lake evaporation calculation are highlighted. (ft = feet; cfs = cubic feet per second)

Table A2. Evaporation data for period **Prior** to application of evaporation suppressant to Lake Arrowhead.

Date	Time Period [days]	Lake Kickapoo Evaporation [inches]	Lake Arrowhead Evaporation [inches]	Ratio of Evaporations (Arrowhead/Kickapoo) [unitless]
June 26 to July 2, 2012	7	2.53	1.71	0.678
July 3 to 9, 2012	7	2.15	2.26	1.052
July 17 to23, 2012	7	2.07	1.73	0.834
July 24 to 30, 2012	7	2.91	2.42	0.831
July 31to Aug.6, 2012	7	2.54	2.61	1.029
August 7 to 13, 2012	7	2.43	2.07	0.851
June 25 to July 1, 2013	7	2.66	2.56	0.962
July 2 to 8, 2013	7	1.63	1.84	1.130
Aug. 27 to Sept. 2, 2013	7	1.34	1.61	1.205
September 3 to 9, 2013	7	1.63	1.99	1.223

Step 2. Assemble Lake Arrowhead and Lake Kickapoo evaporation data during application of suppressant to Lake Arrowhead

Evaporation suppressant was applied to Lake Arrowhead from July 23 to October 2, 2014. The City of Wichita Falls recorded daily diversion data for each lake during this time period, allowing lake evaporation to be calculated on a sub-weekly time step (Appendix B includes sample calculations). To find periods when unmeasured inflow and outflow would be minimized, we again considered lake elevations and streamflow at U.S. Geological Survey Gage 07314500 as shown in Figure A3. In order to maintain similar temporal sampling periods for the **Prior** and **During** data sets, we only considered time periods longer than three days. There are four available data points with suitable characteristics (four or more continuous days with little to no precipitation and inflow; Table A3).

Table A3. Evaporation data for period during application of evaporation suppressant to Lake Arrowhead.

Date	Time Period [days]	Lake Kickapoo Evaporation [inches]	Lake Arrowhead Evaporation [inches]	Ratio of Evaporations (Arrowhead/Kickapoo) [unitless]
July 24 to 27, 2014	4	0.88	0.93	1.061
August 18 to 26, 2014	9	3.64	3.22	0.886
September 2 to 6, 2014	5	2.39	1.55	0.649
September 22 to 27, 2014	6	2.02	1.63	0.808

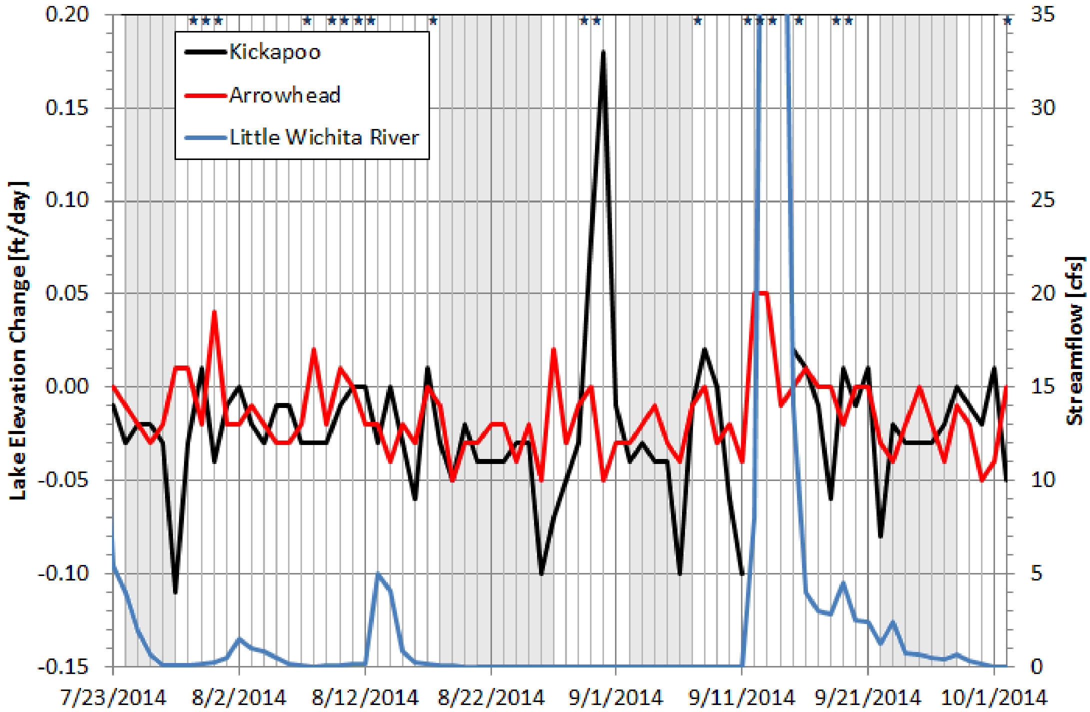

Figure A3. Daily change in lake elevation and streamflow of Little Wichita River in 2014 during application of evaporation suppressant to Lake Arrowhead. Asterisks at top of chart denote days when precipitation was detected on regional radar. Suitable time periods are highlighted. (ft = feet; cfs = cubic feet per second)

Step 3. Test if Lake Kickapoo and Lake Arrowhead evaporation rates are equal prior to application of suppressant.

We performed a rank-sum test on the paired evaporation data for Lake Kickapoo and Lake Arrowhead for the 10 data pairs from the **Prior** data set. We completed the test as described by Helsel and Hirsch (2002) and made no assumptions about the distributions of the data. Table A4 shows the ranks of the **Prior** data. Figure A4 plots the data along with a 1:1 line.

Table A4. Evaporation data and ranks for period prior to application of evaporation suppressant .

Date	Lake Kickapoo Evaporation [inches]	Rank	Lake Arrowhead Evaporation [inches]	Rank
June 26 to July 2, 2012	2.53	15	1.71	5
July 3 to 9, 2012	2.15	11	2.26	12
July 17 to 23, 2012	2.07	9½	1.73	6
July 24 to 30, 2012	2.91	20	2.42	13
July 31 to Aug.6, 2012	2.54	16	2.61	18
August 7 to13, 2012	2.43	14	2.06	9½
June 25 to -July 1, 2013	2.66	19	2.55	17
July 2 to 8, 2013	1.63	3½	1.83	7
Aug. 27 to Sept. 2, 2013	1.34	1	1.61	2
September 3 to 9, 2013	1.63	3½	1.99	8
Sum of Ranks		112½		97½

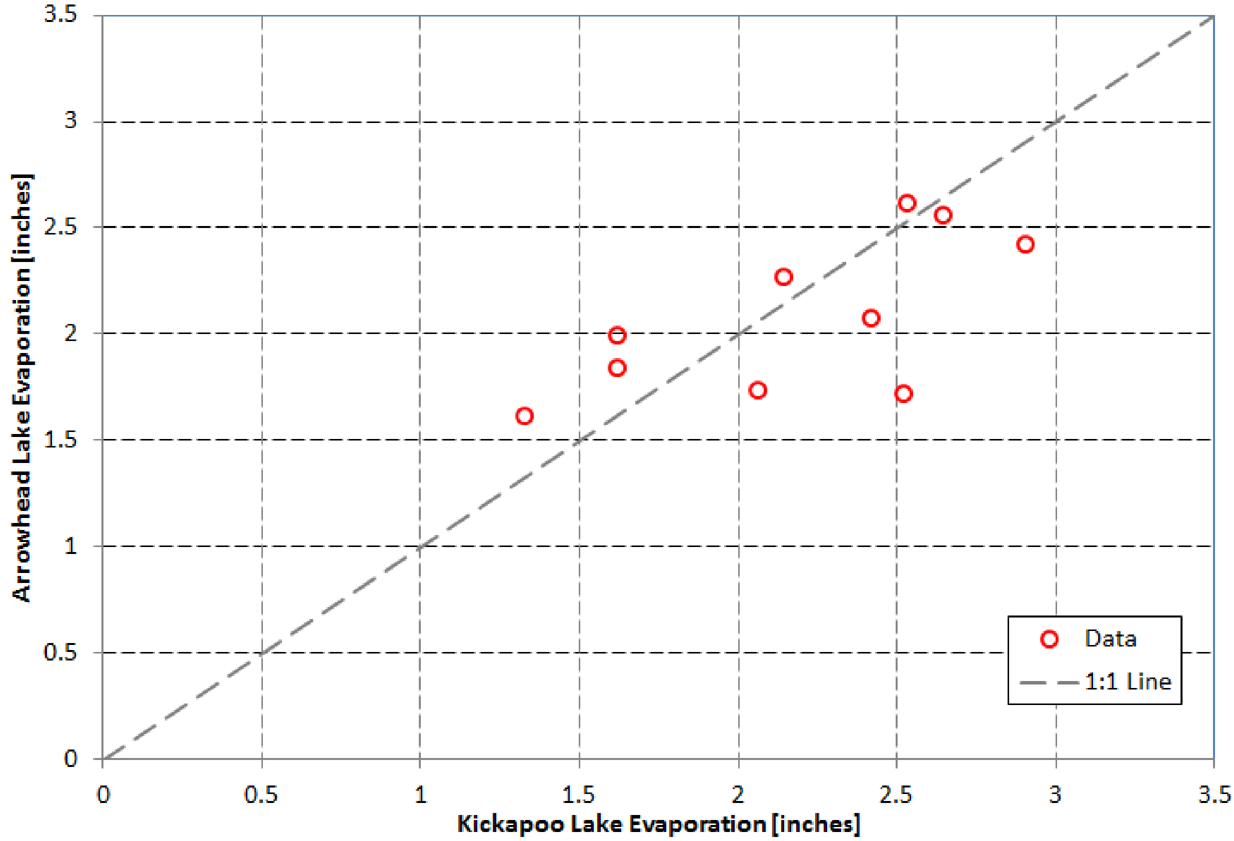

Figure A4. June through September lake evaporation data for Lakes Arrowhead and Kickapoo prior to application of suppressant to Lake Arrowhead.

As provided by Helsel and Hirsch (2002, Appendix B.4), the smallest critical values for the sum of ranks when comparing two sets of data with 10 data points each would be 91 and 119. Since the sum of ranks for both sets falls within this range, we accept the hypothesis that the probability of the evaporation rate of Lake Kickapoo being less or more than the evaporation rate of Lake Arrowhead (during the months of June and September and without application of evaporation suppressant to Lake Arrowhead) is 50:50. In other words, Lake Kickapoo makes a good "Control" for evaporation suppression studies of Lake Arrowhead. Essentially, prior to application of evaporation suppressant to Lake Arrowhead, for the June through September timeframe, it's a coin flip as to which lake will have the higher evaporation rate.

Step 4. Test if Lake Kickapoo and Lake Arrowhead evaporation rates are equal during application of suppressant to Lake Arrowhead.

We performed a rank-sum test on the paired evaporation data for Lake Kickapoo and Lake Arrowhead for the four data pairs from the **During** data set. We completed the test as described by Helsel and Hirsch (2002) (Table A5, Figure A5).

Table 5. Evaporation data and ranks for period during to application of evaporation suppressant to Lake Arrowhead.

Date	Lake Kickapoo Evaporation [inches]	Rank	Lake Arrowhead Evaporation [inches]	Rank
July 24 to 27, 2014	0.88	1	0.93	2
August 18 to 26,2014	3.64	8	3.22	7
September 1 to 6, 2014	2.39	6	1.55	3
September 22 to 27, 2014	2.02	5	1.63	4
Sum of Ranks		20		16

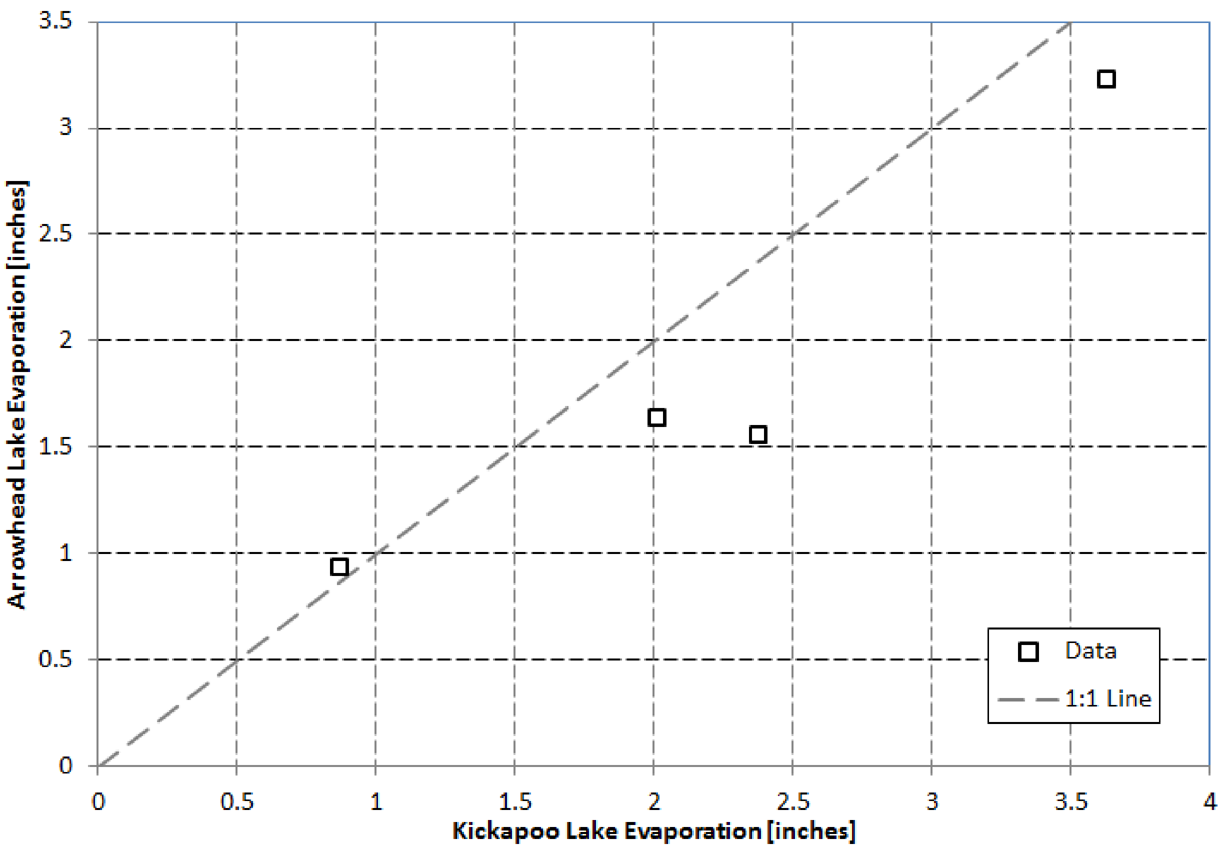

Figure A5. Lake evaporation data for Lakes Kickapoo and Arrowhead during application of suppressant to Lake Arrowhead.

As provided by Helsel and Hirsch (2002, Appendix B.4), the smallest critical values for the sum of ranks when comparing two sets of data with 4 data points each would be 14 and 22. Since the sum of ranks for both sets falls within this range, we cannot reject the hypothesis that the probability of the evaporation rate of Lake Kickapoo being less or more than the evaporation rate of Lake Arrowhead during the application of evaporation suppressant to Lake Arrowhead is still 50:50. The data (Figure A5) seem to present some evidence that Lake Arrowhead evaporation was reduced (in 3 out of 4 pairs Lake Arrowhead evaporation is less than that for Lake Kickapoo), but there is not enough data to prove this point conclusively. Therefore, we are in a similar situation to flipping a coin. A standard coin would have a 50:50 chance of being heads or tails (**Prior** data indicates that without evaporation suppressant applied to Lake Arrowhead, there's about a 50:50 chance that Lake Kickapoo evaporation is greater than that from Lake Arrowhead). If we flipped the coin 100 times and it came up heads 75 times, we'd have enough information to reject the hypothesis that the coin has a 50:50 chance of being heads or tails. But if we flip the coin four times and it comes up heads three times, that's not enough trials to prove there's anything unusual going on with our coin.

Step 5. "Normalize" both data sets and investigate further

In comparing the two data sets, there is a little bit of a mismatch as the **Prior** data set provides evaporation data for seven day periods while the **During** data set provides data on a mixed duration of time periods, from 4 to 9 days. Also, there is some concern that weather conditions in 2014 may have been different than in previous years (for example, 2014 may have been more humid than 2012 or 2013). In order to account for both these concerns, we "normalized" lake evaporation data in both data sets by dividing lake evaporation for Lake Arrowhead by that of Lake Kickapoo for the same time period. This minimizes the impact of differences in time period or weather conditions on the two data sets.

We carried out further analysis on the ratio of Lake Arrowhead to Lake Kickapoo evaporation (Table A6 Figure A6)..

Table A6. Statistics calculated for ratio of lake evaporation data sets.

Ratio of Lake Evaporation (Arrowhead/Kickapoo)	**Prior**	**During**
Count	10	4
Mean	0.979	0.851
Standard Deviation	0.180	0.171
Minimum	0.678	0.649
25th Percentile	0.839	0.769
Median	0.995	0.847
75th Percentile	1.110	0.929
Maximum	1.223	1.061

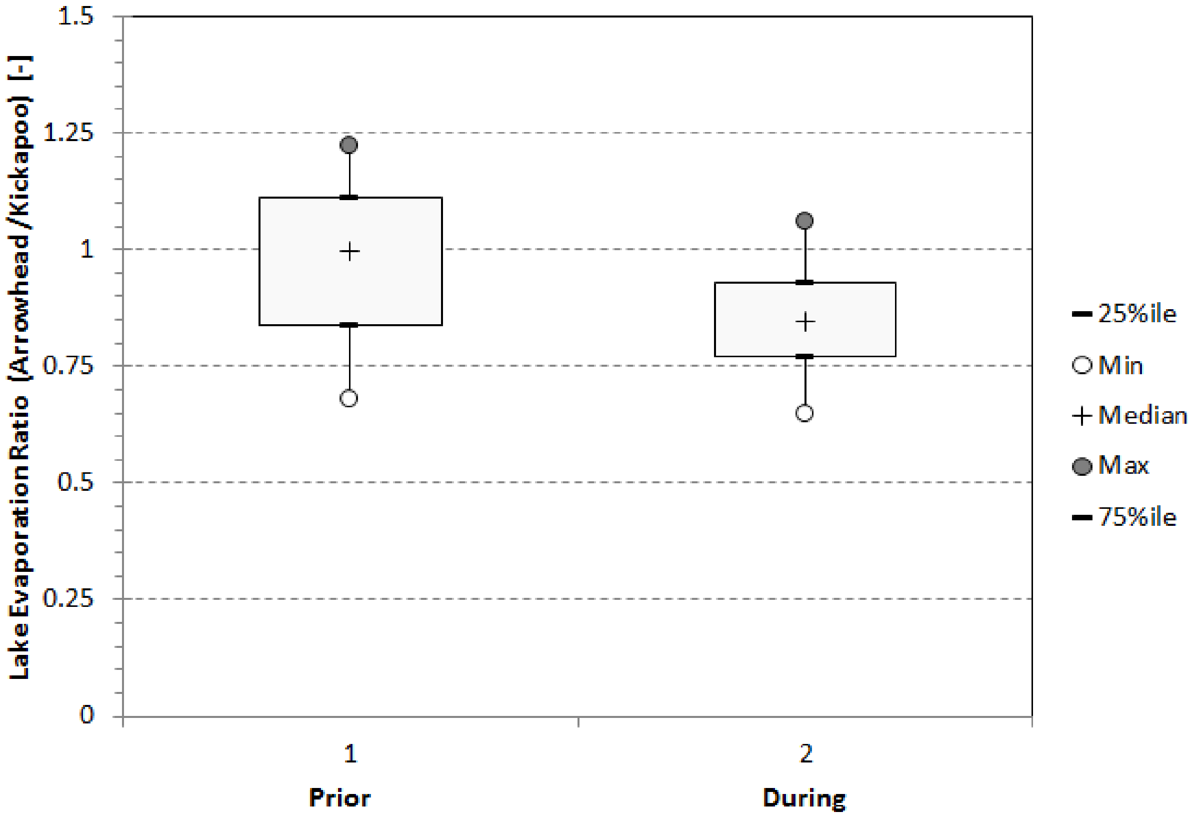

Figure A6. Box plots of two lake evaporation data sets. (25%ile = 25th percentile; Min = minimum; Max = maximum; 75%ile = 75th percentile)

We developed a Q-Q plot (quantiles of one data set versus the quantiles of another) following the procedures of Helsel and Hirsch (2002) (Figure A7). As noted by Helsel and Hirsch (2002), if the data sets come from the same distribution, the quantile pairs would plot along a straight 1:1 line. Additionally, if the data sets differ only by an additive amount, the pairs will fall along a line parallel to but offset from the 1:1 line. This appears to be the case with the **Prior** and **During** data sets, suggesting that the ratio between Lake Arrowhead and Lake Kickapoo evaporation is reduced by a relatively constant amount during application of the suppressant.

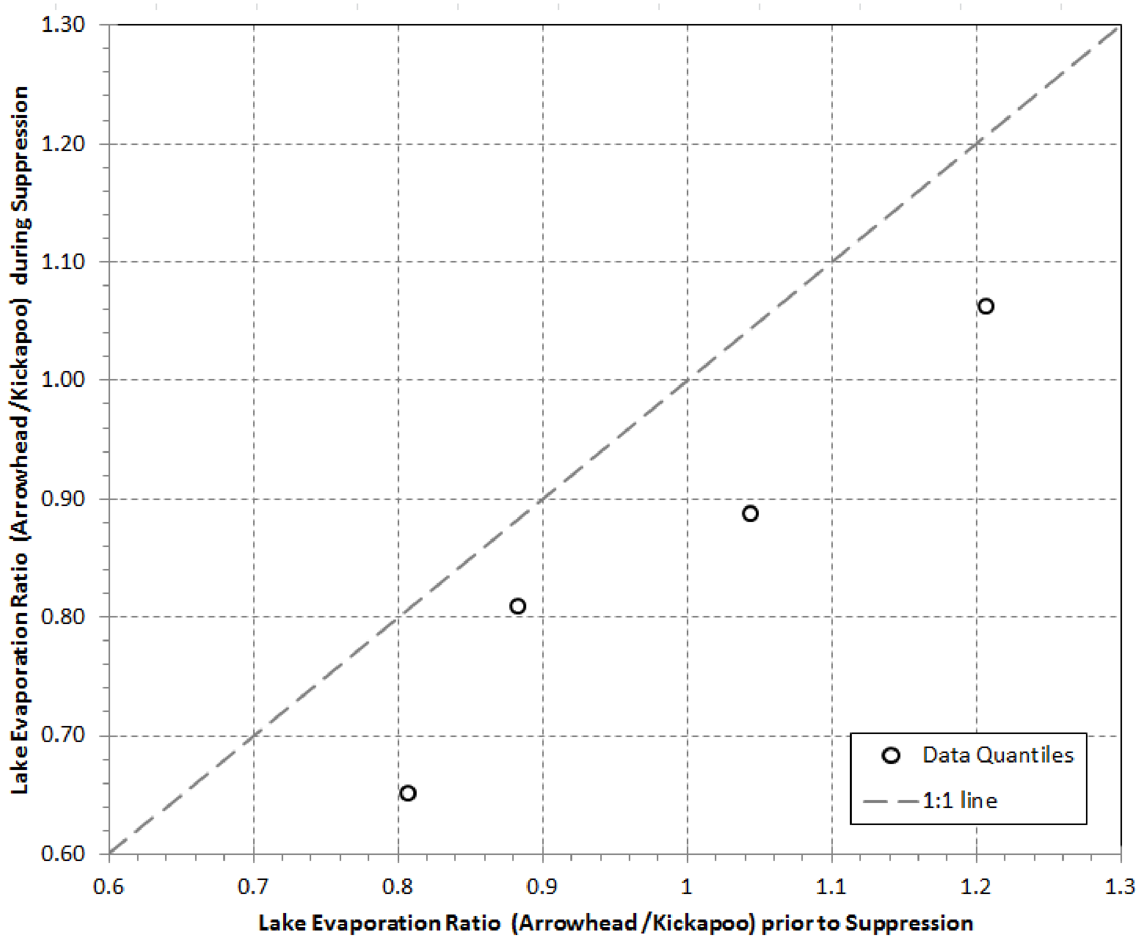

Figure A7. Q-Q plot of lake evaporation ratios (Arrowhead/Kickapoo) prior to and during application of suppressant to Lake Arrowhead.

Step 6. Determine if the ratio data are normally distributed

We examined both ratio data sets to see if they were normally distributed. We began by plotting the data against normal quantiles (Figure A8; also plotted on this figure is a line where the data would be expected to fall if the data were normally distributed with the same mean and standard deviation as each data set). The correlation coefficient between the **Prior** and **During** data sets and a corresponding normal distribution with the same mean and standard deviation are 0.982 and 0.996, respectively. Based on a probability plot correlation coefficient test (described in Helsel and Hirsch 2002), both data sets are deemed to be normally distributed. This is good news as it allows us to do some additional tests on the data. Note: Both a Kolmogorov-Smirnov Comparison Test and a Lilliefors Test for Normality point to the larger data set (**Prior** with n=10) being normally distributed. However, the **During** data set (n=4) is too small to be tested for normality with these methods.

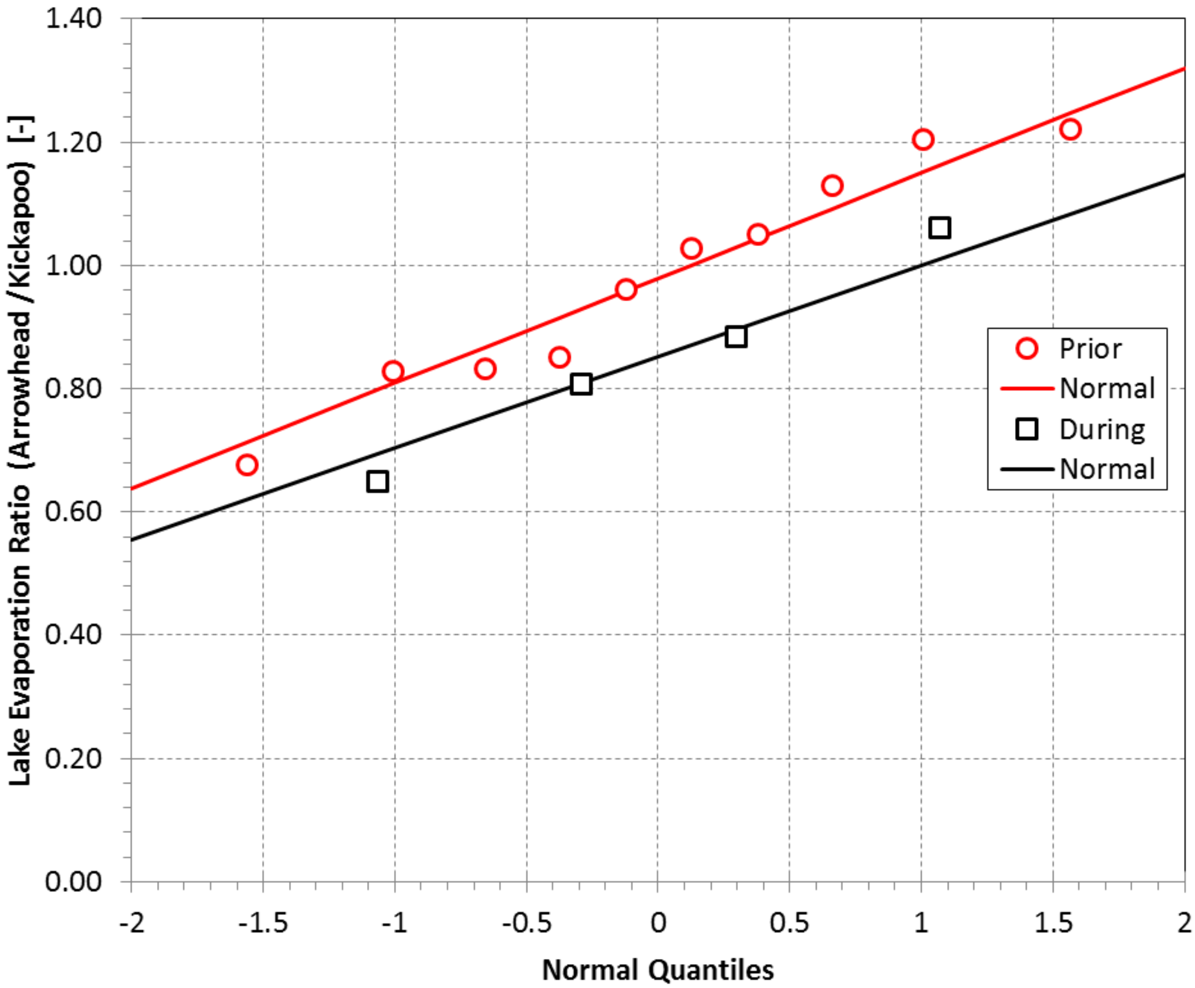

Figure A8. Lake evaporation data plotted against normal quantiles.

Step 7. Use Student's t-test to test if application of suppressant lowered evaporation of Lake Arrowhead

Since we can assume the ratio between Lake Arrowhead and Kickapoo evaporation is normally distributed (both prior to and during the application of suppressant to Lake Arrowhead), we can apply Student's t-test. This test has more investigational power to compare two data sets than the rank-sum test, but the data must be normally distributed. The t-test followed procedures described by Helsel and Hirsch (2002) for data sets with different variances. We computed the t statistic to be 1.249 and the degrees of freedom to be 5.853. If there is no real difference in the evaporation rate from Lake Arrowhead with and without the suppressant, there is only a 13 percent chance that we could have gotten the same four ratios (or lower) by randomly sampling the data. We are therefore 87 percent confident that evaporation from Lake Arrowhead has been reduced by the application of the suppressant. Note that some observers may desire a confidence level of 95 percent or greater to declare a result "statistically significant." Due to the small number of data points in the **During** and **Prior** data sets, that level of confidence is not achieved. However, at a lesser confidence level (87 percent) the data does support the hypothesis that application of the suppressant has reduced evaporation from Lake Arrowhead.

Step 8. Confidence interval on difference between the means

As noted by Helsel and Hirsch (2002), the most efficient estimator of the difference between two normally distributed data sets is just the difference of the means. In our case, prior to application of suppressant to Lake Arrowhead, the mean of the ratio of Lake Arrowhead to Lake Kickapoo evaporation was 0.979. During the application of suppressant, the mean of the ratio was reduced to 0.851. The reduction in evaporation ratio is therefore 0.128. We calculated confidence intervals on this reduction as described by Helsel and Hirsch (2002). The 50 percent confidence interval for the reduction of Lake Arrowhead to Lake Kickapoo evaporation ranges from 0.054 to 0.202. Alternatively, there's a 50-percent chance that similar data could have been obtained even though the suppressant accounts for greater than a 0.202 reduction in the ratio of Lake Arrowhead to Lake Kickapoo evaporation or the reduction is less than 0.054 (including actually increasing the evaporation ratio).

The confidence interval is large for a very low degree of confidence because there are only 10 data points in the **Prior** data set and 4 in the **During** data set. Increasing the confidence to 74 percent requires moving the upper and lower limits of the change in ratio out even farther to between 0 (no change in the ratio) to 0.256. In other words, there is a 74 percent chance that the real change in the mean of the evaporation ratio is between 0 and 0.256. There would also be a 13 percent chance that the change in evaporation ratio is less than zero (the suppressant actually caused an increase in the evaporation ratio and our data points were just too few to pick this up) and a 13 percent chance the change of evaporation was even greater than 0.256 (again because our data points were just too few to pick this up).

For higher levels of confidence (such as 90 and 95 percent), the range of possible changes in the ratio of evaporation from lakes Arrowhead and Kickapoo becomes larger, including negative values. At these very high levels of confidence, it is not possible to eliminate the possibility that the suppressant had no effect or may even have increased evaporation. Nevertheless, at a more modest confidence level, the data does support the hypothesis that application of the suppressant reduced evaporation from Lake Arrowhead.

Tabel A7. Confidence intervals for the change in lake evaporation ratio (Arrowhead/Kickapoo) from the periods prior to during application of suppressant.

	Change in Ratio of Arrowhead to Kickapoo Evaporation (Prior – During)	
Confidence	Lower Bound	Upper Bound
50 percent	0.054	0.202
74 percent	0.000	0.256
90 percent	-0.072	0.328
95 percent	-0.125	0.381

Data Sources

Lake Kickapoo elevation
U.S. Geological Survey Gage 0731400, Lake Kickapoo near Archer, TX
http://waterdata.usgs.gov/tx/nwis/uv/?site_no=07314000&PARAmeter_cd=00062,72020,00054

Lake Kickapoo elevation-area-capacity table
2013 TWDB survey
http://www.waterdatafortexas.org/reservoirs/individual/kickapoo/rating-curve/twdb/2013-09-01

Little Wichita River flow data
U.S. Geological Survey Gage 07314500, Little Wichita River near Archer City, TX
http://waterdata.usgs.gov/tx/nwis/uv/?site_no=07314500&PARAmeter_cd=00065,00060

Lake Arrowhead elevation
U.S. Geological Survey Gage 0731400, Lake Arrowhead near Henrietta, TX
http://waterdata.usgs.gov/tx/nwis/uv/?site_no=07314800&PARAmeter_cd=00062,72020,00054

Lake Arrowhead elevation-area-capacity table
2013 TWDB survey
http://www.waterdatafortexas.org/reservoirs/individual/arrowhead/rating-curve/twdb/2013-09-01

Precipitation maps from weather radar
http://water.weather.gov/precip/

Bibliography

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources, Chapter A3: *in* Techniques of water-resources investigations of the United States Geological Survey, Book 4, Hydrologic analysis and interpretation, U.S. Geological Survey, 522 p. http://pubs.usgs.gov/twri/twri4a3/pdf/twri4a3-new.pdf

Appendix B

ac-ft = acre-feet
Δ = change

Example calculation of Lake Arrowhead evaporation for **Prior** data set.

Date	Lake Elevation [feet]	Lake Volume [ac-ft]	Δ Volume [ac-ft]	Diversions [ac-ft]	Evaporation [ac-ft]	Lake Area [acres]	Evaporation [inches]
6/25/2012	916.77	118,441					
6/26/2012	916.75	118,246	195	65.5	129.5	9,735	0.16
6/27/2012	916.73	118,051	195	65.5	129.5	9,725	0.16
6/28/2012	913.70	117,759	292	65.5	227.5	9,709	0.28
6/29/2012	916.66	117,372	387	65.5	322.5	9,688	0.40
6/30/2012	916.62	116,985	387	65.5	322.5	9,668	0.40
7/1/2012	916.60	116,791	194	65.5	128.5	9,657	0.16
7/2/2012	916.58	116,598	193	65.5	127.5	9,647	0.16
6/26–7/2/2012							1.71

Example calculation of Lake Kickapoo evaporation for **Prior** data set.

Date	Lake Elevation [feet]	Lake Volume [ac-ft]	Δ Volume [ac-ft]	Diversions [ac-ft]	Evaporation [ac-ft]	Lake Area [acres]	Evaporation [inches]
6/25/2012	1,035.88	42,318					
6/26/2012	1,035.87	42,280	38	5.1	33	3,789	0.10
6/27/2012	1,035.83	42,129	151	5.1	146	3,780	0.46
6/28/2012	1,035.80	42,015	114	5.1	108	3,773	0.34
6/29/2012	1,035.77	41,902	113	5.1	108	3,766	0.34
6/30/2012	1,035.73	41,752	150	5.1	145	3,757	0.46
7/1/2012	1,035.69	41,602	150	5.1	145	3,748	0.46
7/2/2012	1,035.66	41,489	112	5.1	107	3,741	0.34
6/26–7/2/2012							2.53

Example calculation ratio of Lake Arrowhead to Lake Kickapoo evaporation for **Prior** data set.

Date	Lake Arrowhead Evaporation [inches]	Lake Kickapoo Evaporation [inches]	Ratio of Arrowhead to Kickapoo Evaporation [-]
6/26–7/2/2012	1.71	2.53	0.678

Example calculation of Lake Arrowhead evaporation for **During** data set.

Date	Lake Elevation [feet]	Lake Volume [ac-ft]	Δ Volume [ac-ft]	Diversions [ac-ft]	Evaporation [ac-ft]	Lake Area [acres]	Evaporation [inches]
7/23/2014	907.68	51,040					
7/24/2014	907.67	50,982	57	3.3	54	5,751	0.11
7/25/2014	907.65	50,867	115	3.7	111	5,745	0.23
7/26/2014	907.62	50,695	172	3.8	169	5,737	0.35
7/27/2014	907.60	50,580	115	3.8	111	5,731	0.23
7/24–27/2014							0.93

Example calculation of Lake Kickapoo evaporation for **During** data set.

Date	Lake Elevation [feet]	Lake Volume [ac-ft]	Δ Volume [ac-ft]	Diversions [ac-ft]	Evaporation [ac-ft]	Lake Area [acres]	Evaporation [inches]
7/23/2014	1031.40	27,759					
7/24/2014	1031.37	27,675	84	18.0	66	2792	0.28
7/25/2014	1031.35	27,619	56	0.8	55	2789	0.24
7/26/2014	1031.33	27,564	56	21.1	35	2786	0.15
7/27/2014	1031.30	27,480	84	35.2	48	2782	0.21
7/24–27/2014							0.88

Example calculation of ratio of Lake Arrowhead to Lake Kickapoo evaporation for **During** data set.

Date	Lake Arrowhead Evaporation [inches]	Lake Kickapoo Evaporation [inches]	Ratio of Arrowhead to Kickapoo Evaporation [-]
7/24–27/2014	0.93	0.88	1.061