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THE IMPACTS OF WATER CONSERVATION STRATEGIES ON WATER USE

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THE IMPACTS OF WATER CONSERVATION STRATEGIES ON WATER USE

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ABSTRACT

We assessed impacts on water use resulting from implementation of controlled experiments relating to five different water conservation strategies in five towns within the Ipswich watershed in Massachusetts. The strategies included (1) installation of weather-sensitive irrigation controller switches (WSICS) in residences and municipally-administered athletic fields, (2) conversion from semiannual to monthly water billing of single-family residences, (3) installation of rainwater harvesting systems in residences, (4) two town-administered outreach programs: (a) free home indoor water use audits and water fixture retrofit kits and (b) rebates for low-water-demand toilets and washing machines, (5) soil amendments to improve soil moisture retention and reduce water demand at a municipal athletic field. Nonparametric statistical methods are generally used to evaluate the effectiveness of these conservation strategies in reducing water use. The variation in water savings attributed to WSICS systems in residential settings is large and, therefore, the overall savings were found to be insignificant, whereas the municipal WSCIS systems significantly reduced water use. The residential properties with high irrigation demand were found to be more likely than low water users to experience a substantial demand decrease when equipped with the WSICS. A town-wide summer restriction on outdoor watering obscured the ability to detect summer savings associated with increased billing frequency. Interestingly, increased billing frequency corresponded to increased winter water use. Rainwater harvesting provided substantial rainwater use, but these volumes were small relative to total domestic water use and relative to the natural fluctuations in domestic water use. This difference in scale impeded our overall assessment of domestic water savings resulting from rainwater use. Both the residential audits/retrofit

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and rebate programs resulted in significant water savings. A modeling approach showed potential water savings from soil amendments in ball fields. Overall, controlled experiments and associated hypothesis tests relating to water conservation strategies show promise for elucidating these strategies' impacts on water use behavior and for the design of future experiments.

KEY TERMS: water conservation, water demand management, water resource planning, nonparametric statistics

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1. INTRODUCTION

The Ipswich watershed, situated north of metropolitan Boston, has experienced unnaturally low or no flows during some summer months in recent years owing in part, to increases in public water supplies (Canfield et al., 1999; Zarriello and Ries, 2000). The ongoing streamflow depletion has raised awareness of the importance of water demand management among the water authorities, and as a result, the Massachusetts Department of Conservation and Recreation (DCR) has launched a project, funded by the U.S. Environmental Protection Agency (EPA), in an attempt to identify strategies that could help restore instream flows to the Ipswich River. This study employs mostly nonparametric statistical methods to evaluate the effectiveness of five water conservation strategies implemented by the DCR for their ability to achieve water savings. The five strategies are (1) installation of weather-sensitive irrigation controller switches (WSICS) at residences and at municipal athletic fields, (2) conversion from semiannual water billing to monthly billing at residences, (3) installation of rainwater harvesting systems at residences, (4) town-administered programs to provide (a) home indoor water use audits and fixture retrofit kits and (b) rebates for low-water-demand toilets and washing machines, and (5) soil amendments to improve moisture retention and reduce water demand at a municipal athletic field.

Vickers (2001) has reviewed approaches relating to water conservation strategies for municipal, industrial and residential uses. Hilaire et al. (2008) have summarized factors impacting the efficiency of water use in the urban landscape: water conservation strategies, landscape design, economic and noneconomic incentives, irrigation/water application and reuse technologies, people-plants relationship. Most previous research on water conservation strategies involves price incentives. Literature on the price elasticity of water use – impact of water price on water demand – is so well developed that meta-analysis is now possible (for example, see the meta-analysis of 64 previous studies by Dalhuisen et al. 2003). A review of research relating to non-price water conservation strategies, in which price incentives are not used, reveals fewer studies. We note three general approaches to non-price water conservation research: (1) behavioral approaches (2) retrospective analyses and (3) controlled experiments. Examples of the first approach are provided by Corral-Verdugo and Frias-Armena (2006) and others who have evaluated the impact of social norms (an understanding of the attitudes and behavior of others) on water conservation behavior. Similarly, Atwood et al. (2007) and others have identified key behavioral, community, and other socio-economic factors which impact water conservation, such as gender, environmental attitudes, and neighborhood features. Gilg and Barr (2006) have provided a review of research which summarizes behavioral attitudes toward water conservation. Most previous behavioral research on water conservation consists of controlled experimental designs based on a combination of surveys and multivariate statistical analyses.

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A second approach to non-price water conservation research involves a retrospective analysis of previous water use behavior using available data. For example, Kenney et al. (2004) showed the importance of water-use restrictions in reducing water demands during a drought experienced by 8 Colorado cities. Most retrospective research on non-price water conservation strategies has developed multivariate relationships for predicting residential water demand as a function of conservation efforts in addition to numerous other factors or explanatory variables. For example, some of the combinations of explanatory variables considered for predicting water demand, in addition to conservation efforts include price, weather, demographic characteristics (Kenney et al., 2008); price, public information (Smith and Wang, 2008; Wang et al., 1999); price, weather, household income, municipalities, public information, education (Michelsen et al., 1999); price, public information, weather, household characteristics, water use restriction and ration (Renwick and Green, 1999); or price, public information, weather, household characteristics, use restriction, ration, and month (Renwick and Archibald, 1998). For those cited studies, the demand elasticity in response to conservation efforts ranged from 0.03 to -4.51 for indoor strategies and 0 (unresponsive) to -4.81 for outdoor strategies. A demand elasticity of magnitude -1 suggests that 1% increase in conservation effort results in 1% decrease in demand.

A third approach to non-price water conservation research, and the approach used here, involves the use of controlled experiments combined with statistical methods. Here controlled experiments are performed with actual water conservation methods. For example, Karpiscak et al. (2001) estimated water savings by monitoring a water conservation demonstration house. The water savings reported by Karpiscak et al. (2001), however, may not be an accurate response to a single water conservation strategy because the synergistic effects associated with multiple water conservation practices implemented inside the demonstration house were not considered. Buchberger and Wells (1996) monitored residential water demand at four households over a one year period and used that information to develop stochastic models of residential water demands. Though their work did not deal directly with water conservation efforts, such research could provide important inputs to future water conservation strategies. Mayer et al. (2003, 2004) and Ayres (1996) have employed t-tests to assess water savings due to various water conservation strategies in an experimental group relative to a control group.

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Although we did find some examples of the type of research we performed here, in which designed experiments are used to evaluate the effectiveness of water conservation technologies and programs using hypothesis tests (Mayer et al., 2003, 2004; Ayres, 1996), the applicability of the t-test used in these studies was not assessed by any investigation of probability distributions of the data sets. The researchers assumed the data had come from a normal distribution without performing normality checks. Here, we have confirmed the suitability of statistical methods and applied them to controlled experiments to assess the effectiveness of each of five independent water conservation strategies. As a result, we were able to evaluate the impact of each water conservation strategy independently. We begin by reviewing the statistical methods employed and providing an overview of the five conservation strategies.

2. METHODOLOGIES

A wide range of statistical methods were considered here due to the different experimental designs and nature of the five water conservation strategies considered. Nonparametric methods are often recommended over parametric methods (Helsel and Hirsch, 2002) when sample sizes are limited and/or in cases when a probability distribution can not be determined for the random variable of concern. Here, we used mostly nonparametric hypothesis tests, because most of the datasets were either too small and/or they violated various assumptions required for parametric hypothesis tests to be meaningful. We assumed, throughout our analyses, that the type I error probability α was 5%.

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We used nonparametric confidence intervals for the true population median because the probability distributions of the original random variables can not be determined. Such confidence intervals for the true population median, shown in many subsequent figures, are used to assess whether the median estimated from one sample differs from the median estimated from another sample. Helsel and Hirsch (2002) suggested that the nonparametric interval for the median can be estimated using the binomial probability distribution. The probability of an observation being above or below the median is equal so that p=0.5. For a sample size n, the cumulative probability p(x) of x observations exceeding the median is then

$$p(x) = \sum_{y=0}^{x} \frac{n!}{y!(n-y)!} 0.5^{y} (1-0.5)^{n-y} \text{ , } \forall x = 1,2,\ldots n \qquad (1)$$

The lower bound of the interval can be estimated using the $(x+1)^{th}$ smallest observation, where x corresponds to p(x)=0.025, which reflects a 2.5% probability in each tail of the distribution of x. The upper bound of the interval can be estimated using the $(n-x)^{th}$ smallest observation. The resulting confidence intervals for the median reflect the distributions of the estimates of medians drawn from any data set of length n. For cases where the sample sizes are large (n>20) one may use a normal approximation to the binomial distribution in (1) leading to the rank corresponding to the lower bound of the interval estimate of:

$$R_l = \frac{n - Z_{0.025} \bullet \sqrt{n}}{2} \quad \text{for n>20} \qquad (2)$$

and the upper bound of the interval estimate is the R_u th smallest observation, where:

$$R_u = \frac{n + Z_{0.025} \bullet \sqrt{n}}{2} + 1 \quad \text{for n>20} \qquad (3)$$

and $Z_{0.025}$=1.96.

In some instances, we were able to employ hypothesis tests based on the assumption of a normal distribution. To check whether observations of a sample are normally distributed, the normal probability plot correlation coefficient (PPCC) was computed and checked against its critical value given in Table 18.3.3 of Stedinger et al. (1993). The normal quantiles were estimated using Blom's unbiased, plotting position for normal variates (Stedinger et al., 1993):

$$p_i = \frac{i - 3/8}{n + 1/4} \qquad (4)$$

where i is the i$^{\text{th}}$ observation when ranked in ascending order.

The hypothesis tests used in this study, corresponding to the various types of comparisons are documented in Table 1. The sign test was chosen over the sign rank test and the paired rank sum test because the latter two assume a symmetrical distribution of the observations and most of our data sets are asymmetrical.

Table 1. The hypothesis tests used in this study are presented by shaded cells.

Comparison between or among	**One sample and two dependent samples**	**Two independent samples**	**More than two independent samples**	**More than two dependent samples**
Non-parametric tests	Signed test [*+]	Rank sum test (or Wilcoxon-Mann-Whitney test) [+]	Kruskal-Wallis test [*+]	Appropriate test is not available [*]
Parametric tests	t test [*+] Paired t test [*+]	Two-sample t test [*+]	One-way ANOVA [*+]	Two-way ANOVA or multi-way ANOVA [*]

[*]: Zar (1999); [+]: Helsel and Hirsch (2002).

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3. WATER SAVINGS ASSOCIATED WITH WATER CONSERVATION STRATEGIES

The following sections summarize the effectiveness of various strategies considered for reducing the overall Ipswich river basin streamflow deficit by reducing water pumped to meet human demand. Due to the critical contribution of outdoor irrigation to the summertime deficit (Ipswich River Watershed Action Plan, 2003), the water conservation strategies piloted by DCR under the EPA grant and evaluated here have a strong emphasis on reducing lawn and athletic field irrigation. The installation of weather-sensitive irrigation controller switches (WSICS) at residences and municipal athletic fields, the installation of rainwater harvesting systems, the introduction of moisture-retaining soil amendments at an athletic field, and the conversion of semi-annual to monthly billing for residents are all strategies designed to mitigate water withdrawals for irrigation purposes, during the summer months. In addition, the home audit/retrofit and appliance rebate programs aim to mitigate withdrawals for indoor water use, year round.

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3.1. Weather Sensitive Irrigation Controller Switches (WSICS)

A total of nine WSICS were evaluated on residential properties and five in municipal athletic fields. These devices (Weather Reach WR-7® by Irrisoft ®) contain an on-site rain gage and receive continuous solar radiation, temperature, relative humidity, and wind data from a regional weather station (town of Ipswich) via wireless transmission. Based on this information, the WSICS device is designed to deliver water only when needed by the landscape.

Residential WSICS

Approximately 150 residences in the town of Reading, MA have exclusive outdoor water meters. Among this group, nine households that met our experimental group criteria had WSICS installed during the summer of 2005. Criteria included continuous ownership and use of an automatic irrigation system since 2001. An additional 71 households with dedicated outdoor meters meeting these criteria were selected as the control group. For this analysis, quarterly outdoor water use records were obtained from the Reading Water Department for all households in the study from January 2001 through November 2007.

For each residence, a single value representing historic ("pre") water use pre-experimental condition was obtained by averaging the annual outdoor water use from 2001 to 2004, and a single value representing water use during the experimental period ("post") was obtained by averaging the annual outdoor use from 2006 and 2007. Data from 2005 were excluded from the analysis due to this being a transitional year. Because a PPCC normality test determined that the control group was not well approximated by a normal distribution, the nonparametric rank sum hypothesis test was used to compare the water use of both the control and experimental groups as shown in Figure 1. There is no statistically significant difference between the water use of the control and experimental groups in either the "pre" or "post" periods, which can be seen visually in Figure 1 with the overlapping confidence intervals. However, a visual assessment of Figure 1 also suggests the WSICS may have reduced the variability of water use among the experimental group, especially among high water-users.

Rank sum tests applied to the rainfall records from a nearby water treatment plant suggest that typical total rainfall and number of days of rain between May 15th and October 15th (the approximate irrigation season) were statistically indistinguishable during the "pre" and "post" periods. Thus, we were comfortable calculating "savings" for each household by subtracting the "post" from the "pre" period water use. The results of a rank sum test do not show that the water savings for households with the WSICS were different than for the control group. The large range associated with the confidence interval (Figure 2) for the median of the experimental group is due to the small experimental sample size, which was limited by project funding. Nevertheless, Figure 2 illustrates that while the average household in the control group saw a drop in water demand of 1.15 HCF (hundred cubit feet) per year between the two time periods, the average WSICS household saw a reduction of 14.37 HCF per year.

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While this difference is not statistically significant, it reflects the fact that households with high “pre” period water demand saw a large reduction in water use post-installation. As shown in Figure 3, when only high “pre” period water users (annual use > 90 HCF) are included in the analysis, the water savings for the experimental group is significantly greater than the control group. We conclude that households with high irrigation water demands are more likely to reduce their water use due to the WSICS installations. Our analysis also highlights the importance of increasing the sample size of the experimental group of households in any future studies.

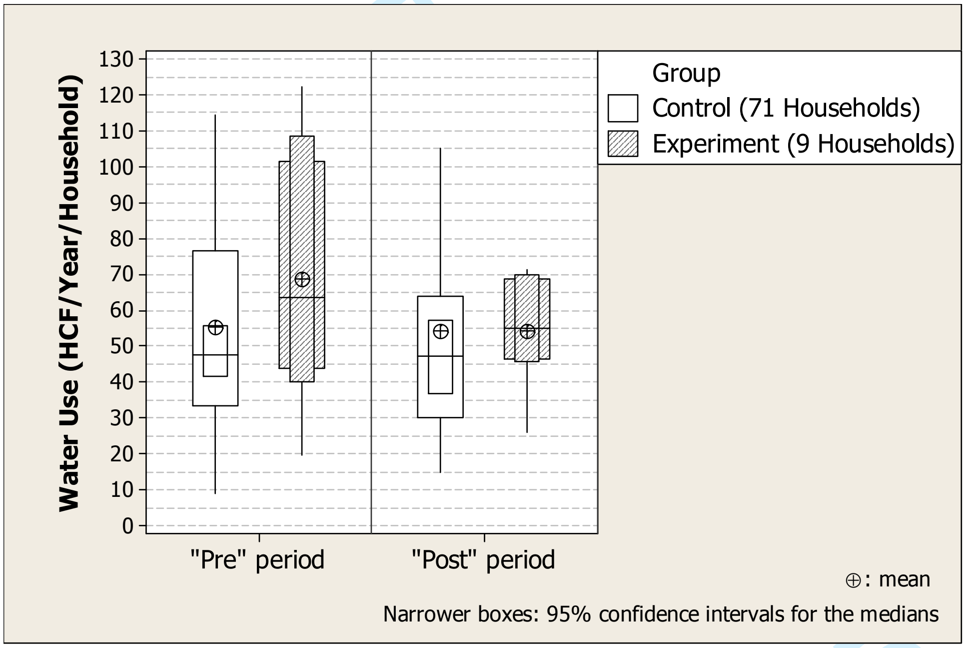

Figure 1. Boxplots comparing annual outdoor water use in the control and experimental groups in both the “pre” (2001~2004) and “post” (2006~2007) periods. HCF represents hundred cubic feet.

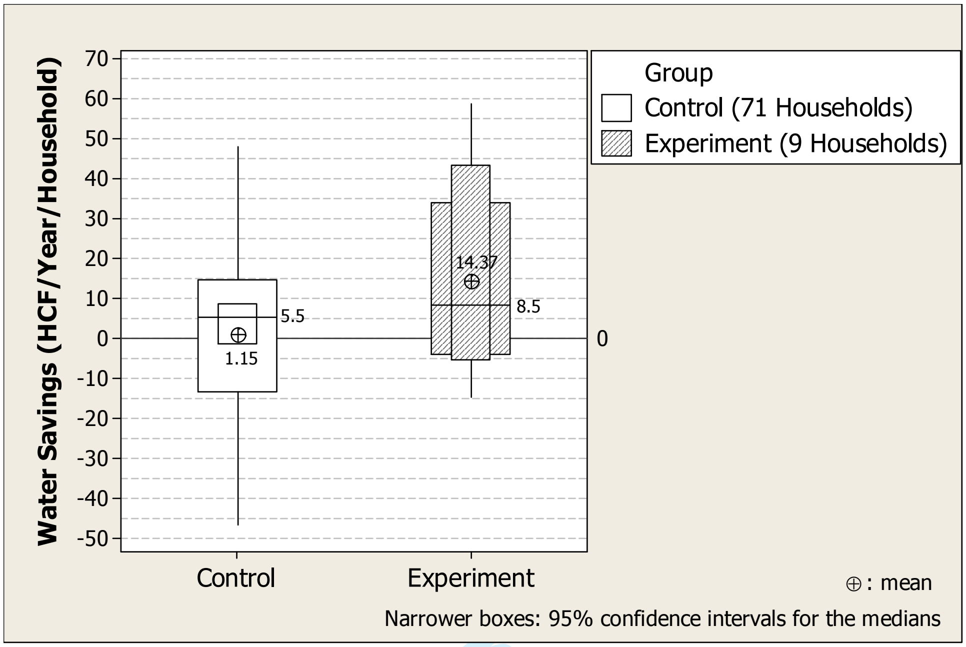

Figure 2. Boxplots showing water savings during the "post" period relative to the "pre" period, in both groups. For each household, this value represents "post" period water use subtracted from "pre" period water use. A value < 0 implies more water was used during the "post" than "pre" period. HCF represents hundred cubic feet.

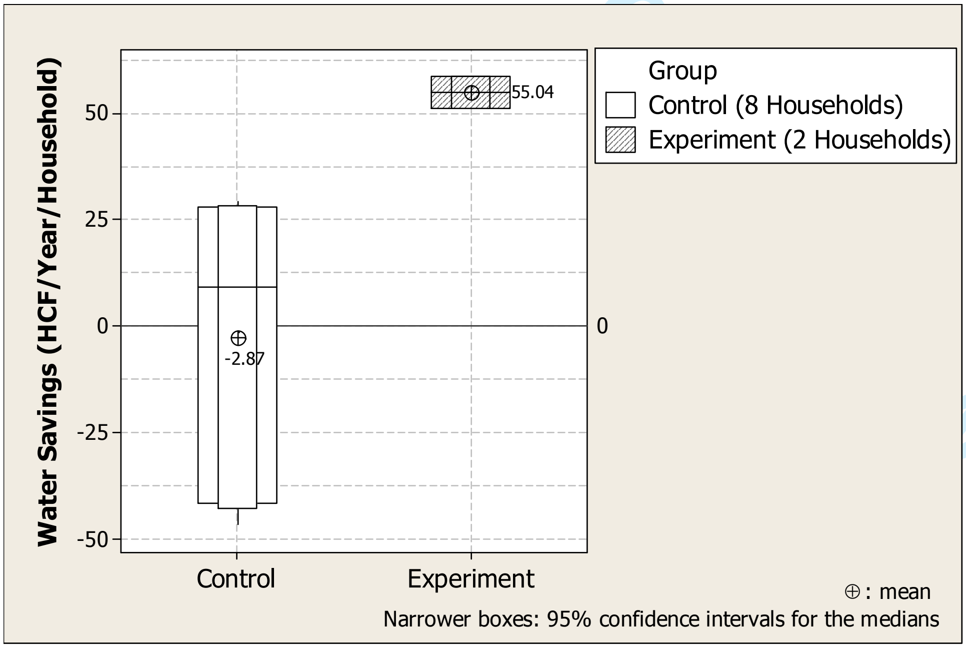

Figure 3. Comparison of the annual outdoor water savings between the control and experimental groups accounting for only high "pre"-period (2001~2004) water users (annual use > 90 HCF). HCF represents hundred cubic feet.

Retrospective Analysis

A retrospective analysis of the WSICS compared actual outdoor water used by each experimental household in 2003 and 2004 to the estimated volume of water that would have been applied by the WSICS during that same period. This analysis required calculating the number of irrigation cycles that would have been triggered for each system, based on: 1) weather data from that period; 2) the algorithm used by the WSICS units to trigger irrigation cycles based on weather data and 3) each system's individual "evapotranspiration (ET) thresholds." ET thresholds are used to set the tolerance for how much estimated evapotranspiration should be allowed before an irrigation cycle is triggered to replenish the loss. The number of triggered irrigation cycles was then converted to a volume for each household by multiplying it by the appropriate per-cycle volume. The latter was determined at each residence by reading the water meter before and after a test irrigation cycle. This approach was only applied to 2003 and 2004 to coincide with the years for which the extensive weather data needed in the algorithm was available. A PPCC normality hypothesis test suggests that the nonparametric sign test is preferred over a parametric test for assessing the difference between the actual and simulated water uses. Although positive overall mean and median water savings (7.98 and 10.34 HCF per household per year respectively) are reported when comparing simulated to actual use, we conclude from the nonparametric sign test that the savings is not significantly different from zero, owing to the large variation in the small sample. When this analysis is applied only to water users with high actual water use (use > 90 HCF) during the years their use exceeded this threshold, the average savings is statistically significant at 47.96 HCF/household/year. However, this sample consisted only of one year of data for each of 3 households.

In summary, two approaches were used: (1) comparing outdoor water use in households where WSICS were installed to outdoor water use in control households, both prior to and after installation, and (2) the retrospective analysis, comparing actual water use to theoretical water use had the WSICS been installed in 2003 and 2004. Both approaches confirm that even though overall water savings for the experimental group is greater than that for the control group, the difference of the savings between the two groups was not statistically significant owing to the highly variable savings in the experimental group, due in part to the small number of experimental households considered in the analysis. WSICS

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were, however, likely to result in water savings when installed at residences with high outdoor water demands. While we did not assess the efficiency of individual watering regimes prior to WSICS installation, the significant response to the systems among the highest water users may suggest over-watering by these households prior to the WSICS installation, as WSICS systems are designed specifically to reduce unnecessary irrigation.

Municipal WSICS

In addition to residential WSICS, five municipal athletic fields across two municipalities (Reading and Middleton, MA) were equipped with WSICS in the summer of 2005. A retrospective analysis was conducted using the same methodology as described above for the residential participants. Hypothetical water use was derived by simulating irrigation triggers that would have been signaled by the WSICS, had they been installed during 2003 and 2004, using weather records from that period and each field's WSICS ET thresholds and irrigation cycle volumes. This simulated use was compared to actual water use for each of the five fields aggregated for 2003 and 2004 (Figure 4). Theoretical water savings were obtained by subtracting simulated use from actual use for each field for each year. Nonparametric tests were used again due to a sample size of 10 (2 years each, for 5 fields). The sign test indicates that a significant positive water savings would have resulted from the WSICS installations. A box plot of the theoretical water savings (Figure 5) indicates that this statistically significant average savings was approximately 162 hundred cubic feet/acre/year.

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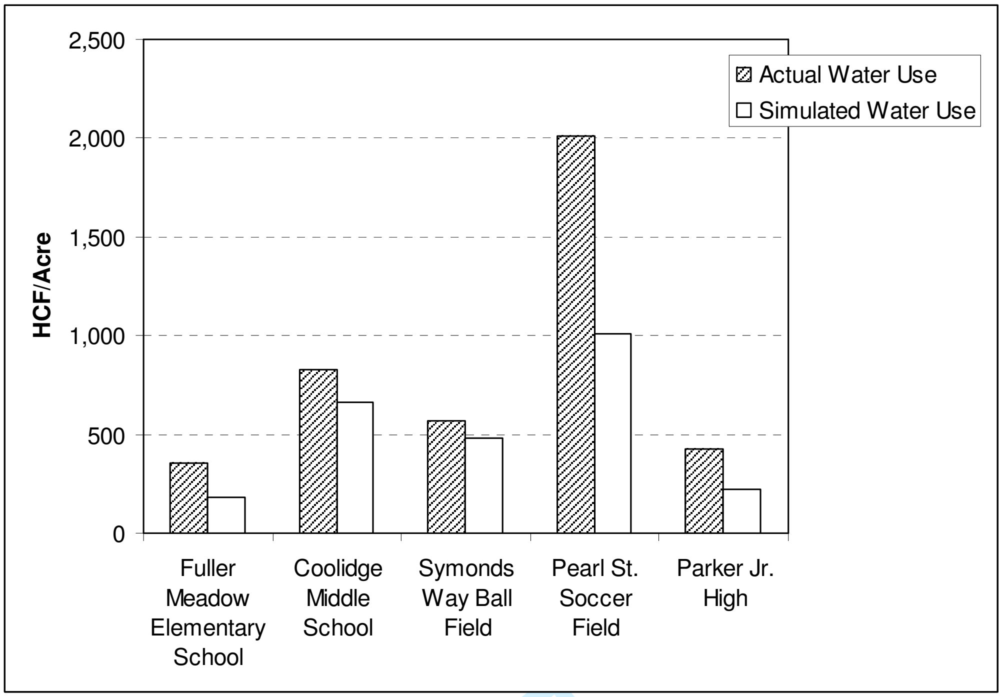

Figure 4. Actual water use (without WSICS) and simulated water use (with WSICS) aggregated for 2003 and 2004 for each ball field.

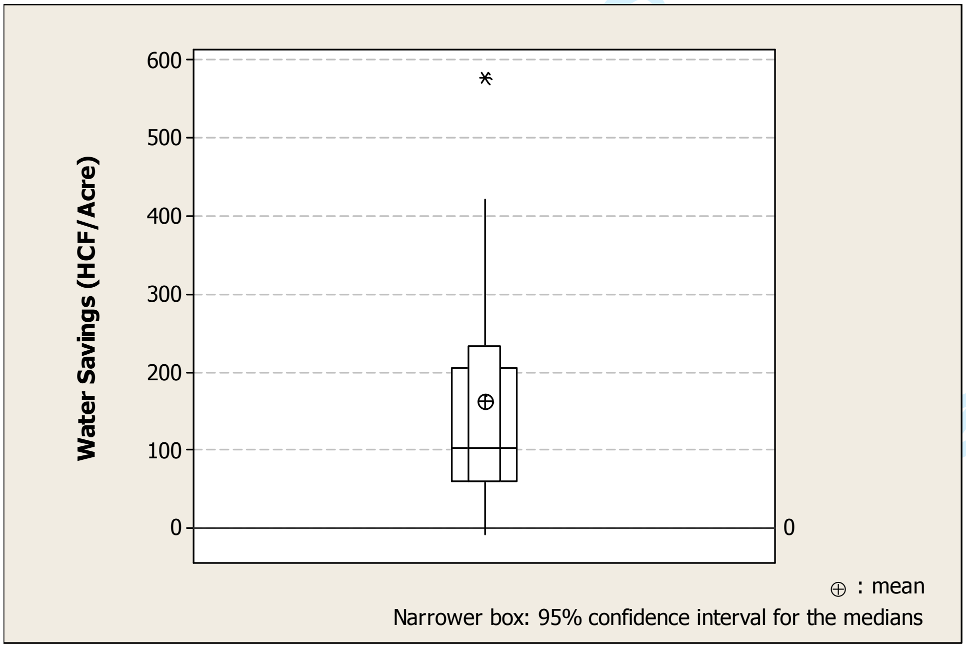

Figure 5. Box plot of theoretical water savings (actual - simulated water use) for each ball field, each year (2003 and 2004). Mean per-acre savings is 162 hundred cubic feet per year.

3.2. Conversion from Semiannual to Monthly Residential Water Billing

The intent of this study was to test whether more frequent water bills would enable customers to recognized sharp increases in water use at the beginning of the irrigation season and respond by voluntarily reducing outdoor uses. The town of Topsfield replaced 500 conventional water meters with radio-read meters. This allowed the water department to read meters more efficiently and, as a result, bill a portion of its customers more frequently. In June 2006, the water department began billing the 500 radio-read customers monthly. The remaining customers continued to be billed semiannually. All water customers were charged using the same progressive block-rate structure and all received a billing insert at the start of the study briefly explaining the importance of water conservation and the purpose of the study. No other specific educational outreach efforts were made, to test whether providing frequent usage feedback alone would be a sufficient trigger for voluntary conservation.

A review of household characteristics was used to confirm that the 500 pilot households represented a reasonable cross-section of the whole town. After screening for continuous ownership over the study period, 406 households who were converted to monthly billing were used as the “pilot” group and 588 of those remaining on a semiannual billing cycle were used as the control. For each household, four mean estimates were derived from water use records dating from April 2000 to November 2007: pre-conversion-summer, pre-conversion-winter, post-conversion summer and post-conversion-winter water use (CF/day/household). Then “summer water savings” was computed as “pre-conversion summer use” – “post-conversion summer use” and “winter water savings” and was computed as “pre-conversion winter use” – “post-conversion winter use”. Normality tests indicate that data are not normal and nonparametric hypothesis tests are, once again, preferred. A sign test confirms that prior to the conversion there is no evidence of differences in either summer or winter water use between the control and pilot groups. Thus we conclude that the water use patterns of the two groups come from the same population.

A regulatory water-use restriction was put into effect by the town during the summers of 2006 and 2007, the same years for which the monthly billing was implemented for the pilot group, which may have masked or eliminated any potential effect from the billing conversion, during the summers. “Summer water savings” was found significant for both groups, and a sign test showed that the summer

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water savings between the two groups were not statistically different (Figure 6). We were not able to separate the simultaneous influences of the billing conversion and water-use restriction on the pilot group's summer water use, and we conclude that the synergistic effect of the combined water use restriction and billing conversion had no greater impact on water use patterns than the water use restriction alone.

Water use restrictions do not apply in the winter, so there are no apparent masking influences on "winter water savings." A sign test showed that the winter water savings of the pilot group was significantly less than that of the control group (Figure 6). The pilot group's relatively higher winter water use may be explained by Bamezai (1995), who found that repairing/retrofitting aging meters appeared to increase measured water use, because the sensitivity of a meter to water flow, especially low flow, declines over time. It is also possible that the decreased winter savings in the pilot group is due to households reacting to extremely low (monthly) winter water bills by increasing water use. However, there are not sufficient data to confirm this hypothesis. In conclusion, the analysis of the effect of monthly billing on summer water use is obscured by simultaneous water use restrictions and possibly by the increased accuracy of newly installed meters, and the overall effectiveness of the monthly billing is inconclusive.

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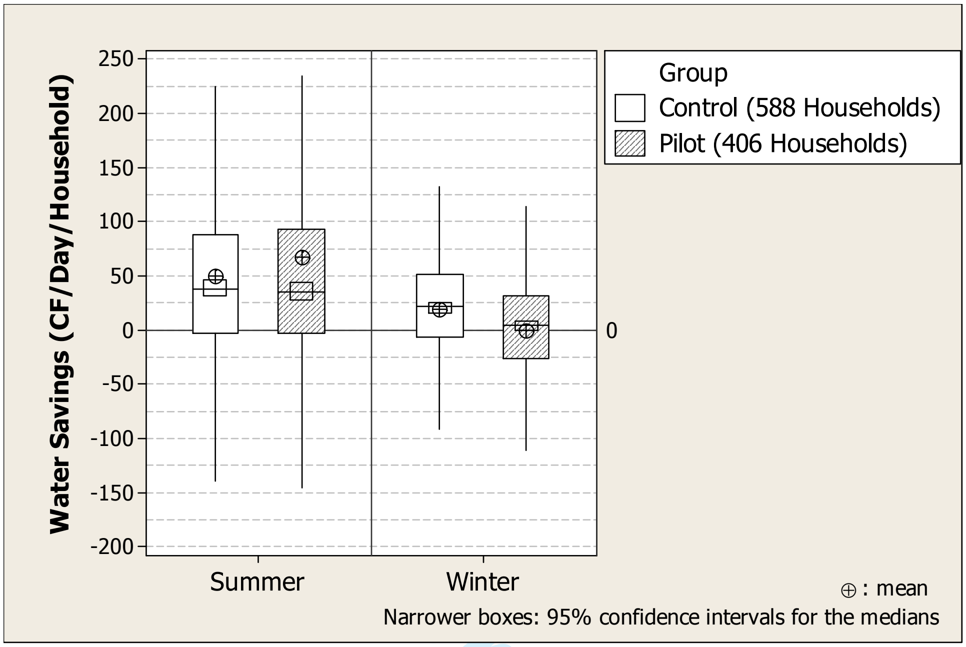

Figure 6. Comparison between the summer and winter water savings in the control group and the pilot group. Savings are defined by subtracting the 2006-2007 (post-conversion) average use from the 2000-2005 (pre-conversion) average use for each household for each season, in both the control and the pilot groups.

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3.3. Rainwater harvesting

Rainwater harvesting systems are designed to capture runoff from rooftops and store the water for nonpotable uses, such as lawn and garden watering. One intent of such systems is to reduce demand on public water supplies by replacing potable water that would otherwise be used for these outdoor purposes. A total of 39 rainwater harvesting systems were installed on residential properties mid April 2006 in the town of Wilmington, MA, based on a lottery among 150 interested households. The systems consist of a storage tank, a pressure pump to aid in water distribution, a spigot for a hose, and a water meter to measure flow pumped from the tanks. Two different sizes of storage tanks were installed: twenty-eight 200-gallon and eleven 800-gallon tanks. Two of the participants with 200-gallon tanks upgraded their storage capacity to 365-gallons and 600-gallons, respectively, using their own funds. Except where otherwise noted, the households with upgraded systems were excluded from the analyses. The rainwater systems were in use during the summers of 2006 and 2007. Total rainwater use from the time each system was turned on in the spring to when it was decommissioned in the fall was recorded for each household for 2006 and 2007. The distribution of the rainwater use observations for both groups are well approximated by a normal distribution. All households used the rainwater systems, and a two sample Students-t hypothesis test on sample means indicates that those with 800-gallon tanks used significantly more rainwater than those with 200-gallon tanks (Figure 7).

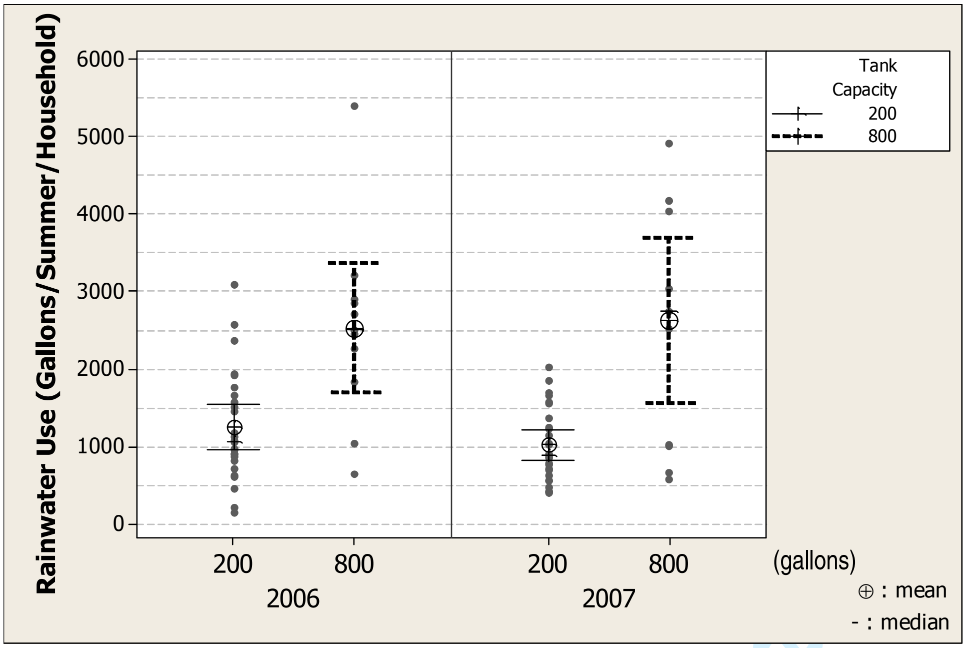

Figure 7. The data and 95% confidence intervals for the mean of the total rainwater used from both sizes of harvesting systems during the summer watering seasons of 2006 and 2007.

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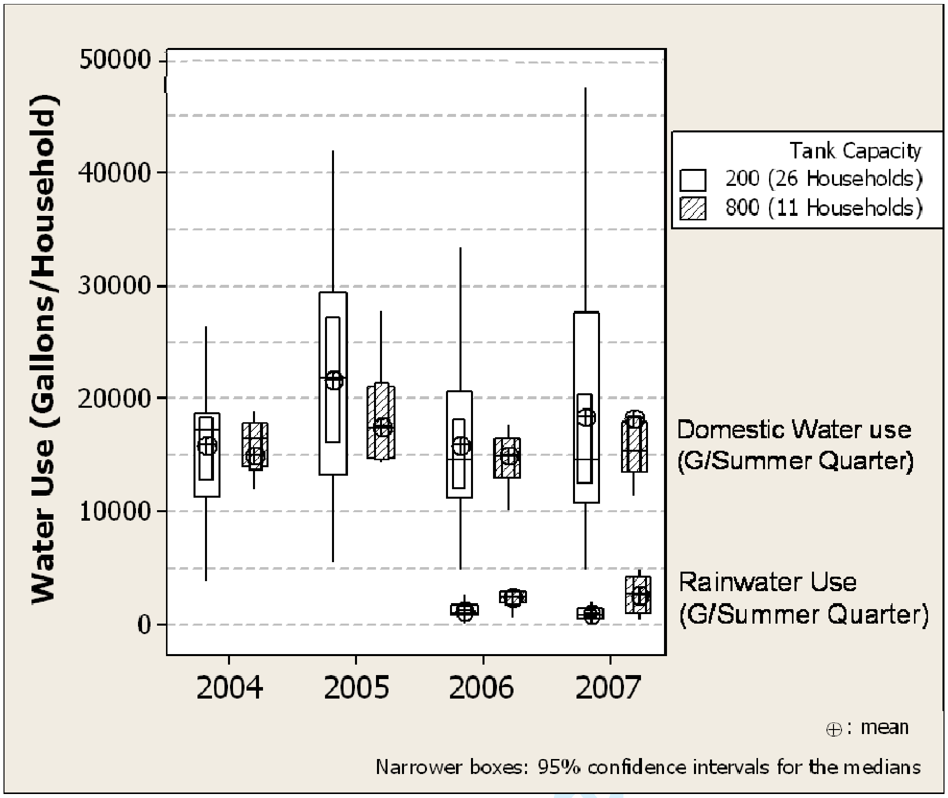

Figure 8. Comparison of scale between household domestic water use and rainwater use.

To assess whether the use of rainwater resulted in a decrease in domestic water use, domestic water use before and after the installation of the rainwater harvesting system was compared for each residential participant. The visual comparison of the domestic water use and the rainwater use in Figure 8 shows that the volumes of rainwater used were generally less than the fluctuation in domestic water use from year to year, making reductions in domestic water use due to rainwater difficult to discern. A rank sum test confirmed that, regardless of the size of the tanks, rainwater systems could not be shown to impact summer domestic water use. However, in a participant survey administered at the end of the program (19 respondents), every respondent stated that at least some of the rainwater they used was a direct substitute for domestic water that they otherwise would have used for the same purpose. Ten respondents (53%) stated that all their rainwater use was a substitute for domestic water use, and an additional 6 (32%) stated that 50%-90% of their rainwater use was a substitute for domestic water use.

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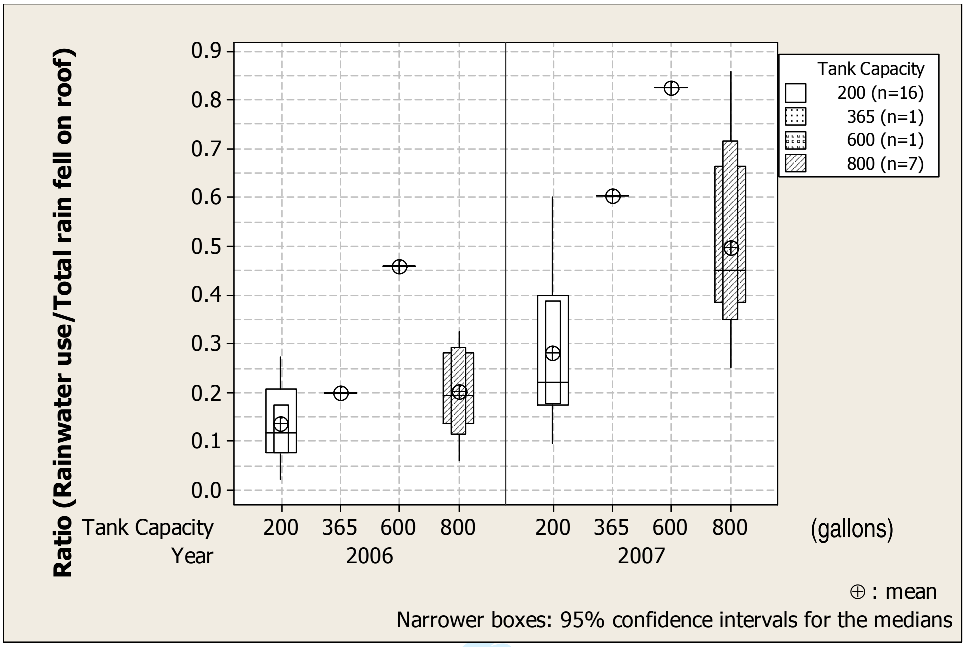

Figure 9. Ratio of rainwater use to total rainfall on contributing roof area during period of summer when system was in use, 2006 and 2007. When the sample size n=1, the interquantile box and confidence interval for the median can not be determined.

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Twenty-five households were able to provide estimates of the roof area contributing to their rainwater collection system. For each of these households, the total volume of rain falling on the contributing area was estimated by multiplying contributing area by daily rainfall depth recorded at a nearby facility for the days the system was in use. Rainwater use efficiency was defined as the ratio of total volume of rainwater used relative to the total volume of rain that fell on the contributing roof area. Each household has a unique rainwater use efficiency, based on the combined influences of system storage capacity, frequency of system use, and the pattern (distribution, intensity, etc.) of rainfall events. A rank sum test of “rainwater use efficiency” by system size (Figure 9) suggests that in 2007 households with 800-gallon systems had statistically higher efficiencies than those with 200-gallon systems, while in 2006 the two groups had statistically equivalent efficiencies. The efficiencies of both groups improved in 2007 relative to 2006, which might be explained by a difference in rainfall patterns between the two years or might indicate a learning curve as participants get used to system operation. As a final observation, the two households with modified systems (365- and 600-gallon systems) demonstrated a relatively high efficiency among all the study participants. A possible explanation is that the participants who took extra care to tailor their systems to their specific needs were able to increase their systems' efficiency.

3.4. Residential Audit/Retrofit and Water Conservation Appliances Rebates

As part of a town-wide water conservation plan, in September of 2003 the town of Reading, MA, began offering water customers free indoor water use audits and water saving retrofit devices tailor-made to the results of the audits. The town also began offering customers rebates for eligible water-efficient appliances (washing machines and toilets) purchased on or after July 1st, 2003. The purpose of the present study was to evaluate the effectiveness of these two programs on town-wide water demand and on the water savings of those households who chose to participate in either or both programs. Participating households were grouped into five mutually exclusive categories of participation: (1) audit/retrofit (AR), (2) audit/retrofit & any type of rebate(s) (AR&R), (3) rebate-toilet(s) (RT), (4) rebate-washing machines(s) (RW), and (5) rebate-toilet(s) & washing machine(s) (RT&W). Participants in the same category should not be interpreted to have exactly the same level of participation. For example, the numbers of low-flush toilets for any two households in the group RT may be different, and the number of retrofit devices installed among households in the group AR are variable. This variability did not hinder analysis, as the intent of the study was not to evaluate savings associated with individual technologies, but rather savings resulting from the programs as a whole, which naturally include varying levels of participation.

Quarterly water use records for the entire town were obtained from February 2001 through May 2007. To isolate indoor water use, only quarters that began on or after October 19th and ended on or before April 14th of any year were included in the analysis. For each household, records dated before the installation of a qualifying rebate device or date of audit are regarded as "pre" winter use, whereas those recorded after are "post" winter use. Savings was determined by subtracting the average of the "post" use records from the average of the "pre" use records.

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The normal PPCC hypothesis test results suggested that nonparametric hypothesis tests are preferred. Sign tests showed statistically significant winter water savings in each conservation category except AR&R (Figure 10 and Table 2a). However, the AR&R households (those participating in both the audit/retrofit and rebate programs) did demonstrate the highest median and second-highest average savings among the categories. The small sample size of this group is likely to explain our inability to detect a statistically significant savings for this category.

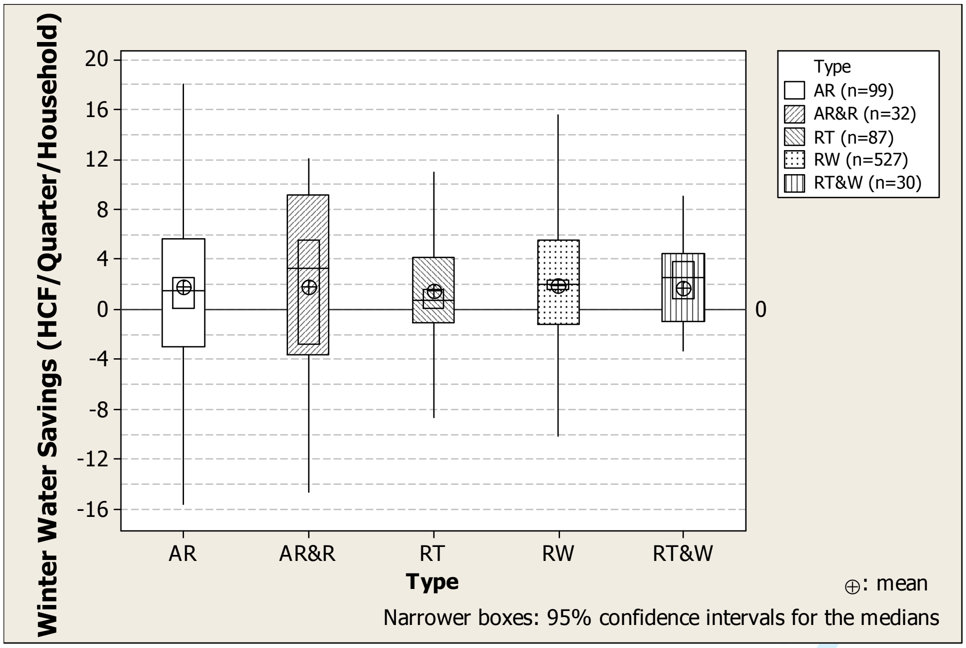

Figure 10. Winter water savings among the five different water conservation treatment categories. Values less than 0 imply an increase in water use after installing a water conservation device or receipt of an audit and retrofit kit. The five categories: audit/retrofit (AR); audit/retrofit & any type of rebate(s) (AR&R); rebate-toilet(s) (RT); rebate-washing machines(s) (RW); and rebate-toilet(s) & washing machine(s) (RT&W)

To evaluate the effect of the two outreach programs on town-wide water use, the overall per-household median savings for participating at any level in either program was multiplied by the number of participating households (Table 2b). The town saved 1,395 HCF/quarter as a result of implementing both programs. Town-wide participation rates are shown for each program and for those participating in both programs (# participating households / # households in town). Participation rates are an important factor in estimating the overall savings that another town might be able to achieve by implementing similar programs. However, it should be noted that Reading saw waves of new participation each time

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the town conducted concerted outreach efforts during the course of the programs. We can assume, then, that the participation rates observed in Reading are closely related to the particular level of outreach effort exerted by the town, and it follows that other towns might be able to increase participation rates with more intensive outreach efforts.

Table 2. (a) Sample size, mean and median water savings for each of the five participation categories, (b) participation rates and town-wide savings for audit/retrofit and appliance rebate programs

(a)

	Savings in HCF/Quarter/household				
	AR	**AR&R**	**RT**	**RW**	**RT&W**
N	99	32	87	527	30
Mean water savings	1.741	1.770	1.391	1.899	1.616
Median winter water savings	1.400	3.250	0.667	2.000	2.500

(b)

	N	**Participation rate based on # households in town (8436)**	**Water savings (HCF/Quarter/Households)**		**Town-wide Savings (HCF/Quarter)**
			Mean	**Median**	
All Levels of participation	775	0.092	1.806	1.800	**1,395**
AR	99	0.012	1.741	1.400	
AR&R	32	0.004	1.770	3.250	
Combined RT, RW, RT&W	644	0.076	1.817	1.833	

3.5. Soil Amendments in Ball Fields

A portion of an 8-acre municipal athletic field complex in the town of North Reading, MA was redeveloped to maximize infiltration and minimize irrigation requirements and application of fertilizer and pesticides by employing the following techniques: (1) soil enhancement with zeolite, an additive that retains moisture, (2) use of drought-resistant turf, and (3) installation of a weather-sensitive irrigation controller switch (WSCIS) (see Section 3.1). The adjacent field, which has identical solar orientation, drainage patterns, and original soil profile, received only the latter two treatments and was used as a control to evaluate the effectiveness of the zeolite additive.

The town progressively adjusted the WSCIS evapotranspiration (ET) thresholds for each field in order to identify the most conservative watering scheme that could still maintain healthy turf. These thresholds set the tolerance for how much estimated evapotranspiration is allowed before an irrigation cycle is triggered to replenish the loss. The optimal thresholds of the zeolite and control fields were found to be 0.35 inches and 0.25 inches, respectively. These settings were used to simulate the number of irrigation cycles that the WSICS would have applied to each field over the five-year period from 2003 to 2007, using historic weather data (see Retrospective Analysis under Section 3.1 for methodology). The number of cycles was then converted to a total annual volume, based on the respective per-cycle volumes measured for each field. Savings was defined by subtracting the total per-acre irrigation volume applied to the zeolite field from that applied to the control field, for each year. The optimum settings resulted in an estimated average annual per-acre savings of approximately 38,000 gallons, or 37% (Table 3). Such substantial savings suggest that zeolite soil amendments may prove to be a very effective means to reduce irrigation demands of athletic fields. However, these results are highly dependent on the optimal ET thresholds observed for each field, based on trial and error and field observation over the course of a few months. To further refine the expected savings achievable through zeolite soil amendments, optimal watering thresholds could be verified by the use of soil moisture sensors. Additionally, observations over a longer time period that encompass greater variability of weather patterns would help verify optimal ET thresholds and refine long-term savings estimates.

Table 3. Simulated irrigation volumes applied to zeolite and control fields (2003 to 2007).

	Threshold (in.)	**Simulated volumes in year (gallons/acre/year)**					
		2003	**2004**	**2005**	**2006**	**2007**	**mean**
Zeolite field	0.35	39,291	54,667	89,454	57,151	99,394	**67,991**
Control field	0.25	97,067	84,623	124,242	84,485	141,636	**106,411**
Savings (control-zeolite)		57,776	29,956	34,788	27,333	42,242	**38,419**
% Savings (savings/control)		59.52%	35.40%	28.00%	32.35%	29.82%	**37.02%**

4. CONCLUSIONS

Hypothesis tests combined with controlled water conservation experiments were used to evaluate water savings associated with five water conservation strategies piloted in communities in the Ipswich watershed in Massachusetts. Mostly nonparametric methods were used due to either small sample sizes

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or data for which probability distributions could not confidently be assigned. Our review of the literature revealed that controlled water conservation experiments combined with nonparametric statistical analyses of the type performed here are not commonly reported. Instead, most previous research has focused on retrospective statistical analyses of water use as well as studies which sought to elucidate behavior and attitudes concerning various water conservation strategies. Our overall findings for each of the five water conservation programs are as follows:

(1) **Weather Sensitive Irrigation Controller Switches** (WSICS): Residential water use patterns were variably impacted by the addition of the WSICS, with some participants showing a decrease and others showing an increase in water use. The WSICS appeared to reduce the variability of water use among residential participants, most notably by causing a reduction in water use of the highest historical water users. Our findings underscore that initial water use patterns are likely to be a prominent factor in determining whether water use will increase or decrease after WSICS installation in a residential setting. Water users who rely on inefficient watering regimes, historically, are more likely to benefit from the WSICS, which may explain why the participants in our study with the highest historical water use showed large and statistically significant water savings after installing the WSICS. In contrast to the residential setting,,WSICS installations at municipal athletic fields resulted in consistent reductions in water application,with an average savings of 162 HCF/acre/year. This suggests that, prior to installation of WSICS, ball fields in our study were more consistently overwatered than residential lawns. This is not surprising, given that towns generally require a high level of turf performance on their athletic fields but lack the staff to frequently adjust irrigation settings in response to weather (such as reducing irrigation volumes after or in anticipation of rain events). To ensure sufficient irrigation without frequent adjustments, systems are set to water frequently, regardless of need. Strict standards for turf performance and limited staff resources are common in municipal settings, suggesting that the savings observed in ball field settings in this study are likely transferable to other ball fields sites.

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(2) **Conversion from Semiannual to Monthly Billing:** Our hypothesis was that more frequent water bills would enable customers to recognize sharp increases in water use at the beginning of the irrigation season and respond by voluntarily reducing outdoor uses. However, our experimental design lacked full controls due the enactment of a town-wide outdoor water-use restriction during the two summers of the monthly billing pilot study. Therefore, both those billed monthly (pilot group) and those who remained on a semi-annual billing cycle (control group) significantly reduced their water use during these summers. There was no statistical difference between the two groups' summer use reductions, suggesting that the combined effect of the water use restriction and monthly billing had no greater impact on water use patterns than the water use restriction alone. Both groups also reduced winter water use during the monthly billing pilot. Interestingly, the pilot group's reduction was less than that of the control group. This could be due to the fact that new meters are more sensitive to (low) water flow than the aging meters (Bamezai, 1995). Another possible explanation is that the pilot group increased winter water use in response to small winter monthly water bills.

(3) **Rainwater Harvesting:** Rainwater was used for outdoor purposes by all participants, and those with 800-gallon systems used significantly more than those with 200-gallon systems. Annual volumes of rainwater used were small compared to domestic water use, and reductions in domestic water use as a result of substitution with rainwater could not be discerned amidst the background fluctuations in domestic water use from year to year. However, a participant survey suggested that for every household, at least some of the rainwater used was a direct substitute for domestic water that would have been used for the same purpose. System efficiency was measured as the ratio of rainwater used relative to the rain that fell on the contributing roof area during the months of system operation. Efficiency of both size systems improved in the program's second year, which may indicate different rainfall patterns between the two years or that there is a learning curve as participants got used to system operation. In the second year, 800-gallon systems were more efficient than 200-gallon systems, while they were statistically equivalent the first year. A possible explanation is that as system efficiency improves, the impact of

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system size becomes more pronounced. Two households that modified their systems' size were among the most efficient, suggesting that efficiency may be improved by tailoring one's systems to one's needs.

(4) **Residential Audit/Retrofit and Water Conservation Appliances Rebates:** Participation in two town-administered water conservation programs (1. free indoor water use audits and fixture retrofit kits; 2. low flow toilet and washing machine rebates) was divided into five categories. Four resulted in modest but significant positive water savings averaging between 1.4 and 1.9 HCF/quarter. Although the fifth participation category (participation in both programs) showed no statistically significant water savings, this group's median and mean savings were ranked the highest and second-highest respectively among all five categories. The finding of non-statistically significant savings of this group appeared to result from the small sample size and large variation in water savings among the participants. In the first four years of program implementation, 9.2% of the town's households participated in one or both of the programs, resulting in an overall average savings of approximately 1,400 HCF/quarter for the town.

(5) **Soil Amendments in Ball Field:** The addition of a moisture and nutrient-retaining additive, zeolite, to the soil of a ball field resulted in healthy turf with less water applied than to an adjacent control field. Based on observed irrigation requirements, the zeolite material was estimated to save approximately 38,000 gallons/acre/year. This represents a reduction of 37% in irrigation volume, suggesting promising water savings from zeolite soil amendments.

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Future research on all of the above strategies could be used to verify or refine the results reported here. To address the specific constraints encountered in this study, the following approaches are suggested. WSICS should be evaluated with larger residential sample sizes and include an assessment of historical irrigation efficiency. The effect of billing frequency on discretionary water use should continue to be evaluated over longer time frames and in the absence of town-enacted outdoor watering restrictions. Additional size categories of rainwater harvesting systems should be evaluated for efficiency under a variety of rainfall conditions and further investigation should be made into the ability of such systems to reduce domestic water use. Town-administered water conservation programs such as Reading's should continue to be evaluated over longer time frames to better understand the long-term potential for savings among participating households and at the town level. Lastly, turf health on the soil-amended and control ball fields was determined by visual inspection. Future research should employ a more sophisticated method for comparing the turf health.

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