PERFORMANCE AND WATER CONSERVATION POTENTIAL OF MULTI-STREAM, MULTI-TRAJECTORY ROTATING SPRINKLERS FOR LANDSCAPE IRRIGATION

K. H. Solomon, J. A. Kissinger, G. P. Farrens, J. Borneman

ABSTRACT. *Multi-stream, multi-trajectory rotating (MSMTR) sprinklers represent an alternative to fixed spray heads for the irrigation of small landscape areas. Preliminary investigations have suggested that MSMTR sprinklers can apply water with higher distribution uniformities than fixed sprays, offering the potential for water conservation. This article presents the results of field audits comparing the performance of fixed spray and MSMTR sprinklers in landscape irrigation. Individual zones were audited before and after a conversion from fixed spray to MSMTR sprinklers. Average low quarter distribution uniformity (DU_{LQ}) improved by 0.26, from 0.44 to 0.70, after the conversions. Average low half run time multiplier (RTM_{LH}) decreased by 0.39. New performance measures, directly related to water conservation, were developed and applied to the field audit data. Water conservation diagrams were used to illustrate performance improvements and the potential for water conservation due to improved performance. Estimated water conservation potential due to the conversion from fixed spray to MSMTR sprinklers depends on pre-conversion uniformity and choice of run time multiplier (RTM). The average water conservation potential estimated for the fixed spray to MSMTR conversion ranged from 22% to 40% of the pre-conversion application depending on pre-conversion choice of RTM. A good single-point estimate for water conservation potential due to fixed spray to MSMTR conversion is 31%. MSMTR sprinklers have lower precipitation rates than fixed spray heads, and may be expected to need longer run times to meet a given required amount. The higher uniformity of the MSMTR sprinkler partially mitigates this. Sample calculations assuming no runoff from the higher precipitation rate fixed sprays indicate the net MSMTR systems may need to run 1.7 to 2.3 times as long as fixed sprays used to run to deliver the same net application.*

Keywords. *Water conservation, Uniformity, Irrigation, Irrigation equipment, Sprinklers, Turf, Landscape.*

Urban water use is an increasingly significant portion of total water use, particularly in the arid West. A major component of urban water use is for irrigation of the urban landscape. Across North America, nearly 60% of residential water use is for outdoor use (Mayer et al., 1999), primarily for landscape irrigation. California's Department of Water Resources (1998) has noted "The greatest potential reduction in urban water use would come from reducing outdoor water use for landscaping." Improvements in the efficiency of landscape irrigation, which could entail either or both improved distribution uniformity and improved scheduling of irrigation, could offer considerable potential for water conservation in the urban sector. It is the goal of this article to investigate one potential avenue towards the improvement of distribution uniformity for landscape irrigation.

IRRIGATION UNIFORMITY AND EFFICIENCY

Burt et al. (1997) provide a good review of irrigation performance measures, including low quarter distribution uniformity (DU_{LQ}, decimal), which they stress is not an efficiency term. Distribution uniformity (DU) measures the evenness with which water is applied to the landscape by an irrigation system (Irrigation Association, 2005). It is measured by conducting an audit, or catch-can test, of the system (Irrigation Association, 2004). DU is the ratio of the average volume of water caught in catch-cans in the least watered areas to the average volume of water caught in catch-cans in the entire area. When the critical, least watered area is taken as the low 25% (the *low quarter*), DU becomes DU_{LQ}, which is the ratio of the average volume caught in the low quarter to the average volume caught overall.

Application efficiency (AE, %), a true efficiency term, is 100% times the ratio of the average depth of irrigation water contributing to the target for an irrigation to the average depth of irrigation water applied. The target for an irrigation is a management selected value which includes consideration of such factors as soil moisture depletion, maintenance leaching fraction, and an allowance for potential rainfall (Burt et al., 1997).

An increase in DU_{LQ} will not necessarily result in water conservation potential. If the water applied is excessive, water may be lost to runoff or deep percolation, resulting in low application efficiency, even if DU_{LQ} is high (Burt et al., 1997). With proper management, avoiding excessive water applications, improved uniformity has the potential to conserve water.

Submitted for review in February 2006 as manuscript number SW 6377; approved for publication by the Soil & Water Division of ASABE in November 2006. Presented at the 2006 ASAE Annual Meeting as Paper No. 062168.

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ISSN 0883−8542

Water destination diagrams have been used to illustrate the partitioning of applied water to beneficial uses, including water stored for plant use and percolation below the root zone beneficial for salt management (leaching), and non-beneficial uses, such as runoff and excess percolation below the root zone. Water destination diagrams graphically illustrate both distribution uniformity and the combined effects of distribution uniformity and management choice of water application amount on such factors as the amount of water percolating below the root zone and the extent to which the soil moisture deficit is satisfied during an irrigation (Burt, 1983, 1989; Burt et al., 1997; Solomon and Kissinger, 2005).

Water conservation diagrams are two water destination diagrams plotted on the same chart, representing conditions before and after an alteration of irrigation equipment or practice, to highlight the consequences of the alteration. For example, the altered equipment or practice may cause a change in the amount of excess deep percolation expected, which would be shown as the difference between the two water destination diagrams. When the alterations are beneficial, particularly when they lead to decreases in water lost to runoff, overspray or deep percolation, the difference between the two water destination diagrams illustrates the magnitude of the decrease in water lost, which represents the potential for water conservation (Solomon and Kissinger, 2005).

Uniformity of Landscape Irrigation Sprinklers

There are generally three types of sprinklers used for turf and landscape irrigation: fixed spray heads, typically used for small and irregularly shaped turf areas, shrubs, and flower beds; geared rotors; and impact rotors; both rotors typically used for large turf areas and ground cover applications (Irrigation Association, 2004). This article considers the performance of fixed spray heads and recently developed alternatives to the fixed spray head for the irrigation of small and irregular turf areas.

There have been a number of investigations into the performance of residential irrigation systems. In Utah, Aurasteh et al. (1984) found average DU_{LQ} values for 20 hand move and solid set homeowner irrigation systems of 0.30 and 0.37, respectively. Pitts et al. (1996) assessed residential lawn sprinkler systems and found an average DU of 0.49. DU was below 0.40 for over 40% of the systems evaluated.

Baum et al. (2002, 2003a, 2003b, 2005) and Dukes et al. (2004) report results of residential irrigation system evaluations made by Florida Mobile Irrigation Labs (FMIL) for a number of counties and years. County average DU_{LQ} values ranged from 0.38 to 0.71. The overall average was 0.55 (Dukes et al., 2004). FMIL audit procedures required that only 16 to 24 catch-cans distributed centrally within the largest zones be used to determine DU_{LQ}. A more extensive evaluation of 25 residences, using 100 to 500 catch-cans distributed evenly across the entire irrigated area, found spray head DU_{LQ} averaged 0.41 and rotor DU_{LQ} averaged 0.49. These values are lower than the FMIL average, which was attributed to the facts that the FMIL procedure tends to under-represent edge effects, difficult areas such as side lawns, and under-irrigated areas (Baum et al., 2003a, 2003b, 2005; Dukes et al., 2004).

Over 400 residential irrigation systems were evaluated in Santa Clara, California. Average values of DU_{LQ} were 0.46 and 0.45 for single-family homes and multi-family complexes, respectively. Roughly one-third, 32% for single-family and 36% for multi-family, of the irrigation systems had DU_{LQ} values below 0.40. Almost two-thirds, 60% for single-family and 63% for multi-family, of the irrigation systems had DU_{LQ} values below 0.50 (M-Cubed et al., 2004).

Mecham (2004) reviewed the results from a large number audits (about 6,800) of landscape irrigation systems from around the country. DU_{LQ} values for residential fixed spray systems (6,649 audits) were typically 0.50 to 0.55. The average value was 0.52. Mecham also reported a wide variation in DU_{LQ} values, from 0.11 to 0.89.

Pitts et al. (1996) attributed low DU values in residential systems evaluated in their study to: lack of maintenance, faulty sprinklers, mixing spray and rotors within the same zone, excessive pressure variation between sprinklers, and poor coverage between sprinklers. Burt et al. (1997) identified these as factors which may reduce sprinkler system DU: improper spacing between sprinklers, different nozzle sizes (could also be nozzles/sprinklers with differing precipitation rates on the same valve), wind, differences in pressure between sprinklers, inadequate overlap at the edge of the irrigated area, nozzle plugging or wear, improper match between nozzle and pressure, and sprinklers deviating from a vertical orientation.

In the Santa Clara, California study, the most frequently observed sprinkler system design or maintenance problem was overspray (46%, combined result for single- and multi-family systems). Overspray does not, however, affect the uniformity of water applied within the irrigated area. The problems that would affect uniformity, in order of frequency observed one or more times in a zone, were: spray pattern blocked (35%), broken/clogged sprinklers (28%), incorrect spray arc (12%), sprinklers not vertical (10%), uneven sprinkler spacing (8%), misting due to high pressure (7%), unequal pressure or discharge rate, heads/nozzles not matched, and sunken heads (6% each).

In the Florida study, pressure differences between the two furthest points in each zone in the residential irrigation systems examined did not differ by more than 10%, so pressure variations did not negatively impact uniformity for these residences. Based on laboratory tests of spray heads, and a comparison of laboratory and field observed performance, it was concluded that for fixed sprays, equipment brand and for some brands, part-circle nozzle type had significant effects on uniformity; for some brands fixed quarter circle nozzles resulted in better uniformity than adjustable nozzles. Pressures below recommended [69 kPa (10 psi) instead of 207 kPa (30 psi)] was found to significantly lower uniformity. The comparison of laboratory and field performance led observers to conclude that irrigation system design (choice of spacing and design allowed pressure differences) was a small component of system nonuniformity (Baum et al., 2003b, 2005; Dukes et al., 2004).

Sprinklers for Small or Irregular Landscape Areas

Fixed spray heads have traditionally been used for small and irregularly shaped landscape areas (Irrigation Association, 2004). Fixed spray heads produce a static spray, distributing water over their entire arc of coverage (1/4, 1/2, full, variable arc, etc.). These may be installed on fixed risers, or in "pop-up" heads, which rise when the water is turned on (Hunter, 2003; Rain Bird, 2004; Toro, 2004). Figure 1 illustrates fixed spray pop-up heads.

Figure 1. Fixed spray heads typically used to irrigate small or irregular landscape areas (Photo courtesy of Water Education Foundation).

An alternate to traditional fixed spray heads for landscape irrigation, a multi-stream, multi-trajectory rotating (MSMTR) sprinkler, is now commercially available. MSMTR sprinklers distribute water in a number of individual streams, of varying trajectories, which turn slowly (fig. 2). These sprinklers are the size of the nozzles in fixed spray heads and thread onto pop-up heads just as spray nozzles do. They can also be threaded onto shrub adapters for installation onto risers (Rain Bird, 2004; Walla Walla Sprinkler Company, 2006).

The MSMTR concept has been implemented commercially as the MP Rotator® by Walla Walla Sprinkler Company and the Rotary Nozzle by Rain Bird®. The distances of throw and operating pressure requirements for these products include those of traditional spray heads, so they can be used as replacements for existing spray heads in system conversions, or can be selected instead of spray heads when new systems are designed. The MP Rotator® and Rotary Nozzle employ different mechanisms to create and control the rotation of the multiple streams. The Rotary Nozzle has a higher flow rate and precipitation rate than the MP Rotator® at equivalent pressures and spacings, though both have lower flow rates and precipitation rates than traditional fixed spray heads (Hunter, 2003; Rain Bird, 2004; Toro, 2004; Walla Walla Sprinkler Company, 2006).

Figure 2. Multi-stream, multi-trajectory rotating (MSMTR) sprinklers. Water leaves the sprinkler in individual streams, which turn slowly, and at multiple trajectory angles (inset) (Photo courtesy of Walla Walla Sprinkler Company).

Another sprinkler with somewhat similar characteristics, the Stream Rotor® manufactured by Toro® (Riverside, Calif.), has been available for some time (Toro, 2004). Direct observation of existing installations and anecdotal evidence from contractors indicate that early versions of the product were multi-stream, but not multi-trajectory, rotating sprinklers. Recent versions of this product incorporate multiple trajectories. However, the Toro® Stream Rotor® has a larger physical size, a greater distance of throw, and requires a higher operating pressure than traditional fixed spray heads. It is not well suited for the irrigation of small turf areas where fixed spray heads are often used, and it is more costly and labor intensive to use as a replacement for fixed spray heads than MSMTR sprinklers. The Toro® Stream Rotor® is not generally regarded as an alternate to traditional fixed spray heads (Budd, 2006).

A comparison of basic parameters for typical fixed spray and MSMTR sprinklers at an operating pressure of 207 kPa (30 psi) is shown in table 1.

There have been indications that the MSMTR sprinkler offers improved low quarter distribution uniformity compared to fixed spray heads in sprinkler systems for landscape irrigation (Blumhardt, 2004; Teske, 2005). Kissinger and Solomon (2005) supported that anecdotal evidence with an analysis of a limited data set from 13 zones irrigated with fixed spray sprinklers at eight sites. They found that replacing fixed spray heads with MSMTR sprinklers (making no other changes) improved average DU_{LQ} by 0.27, resulting in estimated water conservation potential of from 22% to 41%, depending on pre-conversion irrigation management practice.

This article reports on a larger set of field audits (51 zones at 39 sites in 4 states) and the performance and water conservation potential of MSMTR sprinklers compared to fixed spray heads. The objectives of this study are: (1) to compare fixed spray and MSMTR sprinklers under field conditions; (2) to determine if there is a performance differential between the two types of sprinklers; and (3) if a performance differential exists, estimate the water conservation potential associated with that performance differential.

PROCEDURES

To investigate the water conservation potential of MSMTR sprinklers due to improved uniformity, audits were conducted on a variety of existing landscape irrigation systems employing fixed spray heads (The multi-stream, multi-trajectory rotating sprinklers used in these tests were the MP 1000 and MP 2000 Rotator® sprinklers manufactured by the Walla Walla Sprinkler Company, Walla Walla,

Table 1. Flow rate and radius of throw for MSMTR and typical fixed spray sprinklers (full circle) when operated at 207 kPa (30 psi).

Sprinkler	Type	Flow Rate (L/s)	Flow Rate (gpm)	Radius (m)	Radius (ft)	Source[a]
Various	Fixed Spray	0.23	3.65	4.5	15	1,2,3
MP 2000 Rotator®	MSMTR	0.08	1.27	5.2	17	4
Rotary Nozzle R13-18	MSMTR	0.10	1.60	4.8	16	2

[a] [1] Hunter (2003); [2] Rain Bird (2004); [3] Toro (2004); [4] Walla Walla Sprinkler Company (2006).

Table 2. Audits conducted for this study.

Auditor	Individual Zones Audited	Sites	Locations
Kissinger	28	16	Calif.
Farrens[a]	16	6	Wash.
Borneman	7	7	Ariz., Calif., Nev.
Total	51	29	Ariz., Calif., Nev., Wash.

[a] Audits conducted by students under the direction of Farrens.

Washington. At the time these tests were conducted the Rain Bird® Rotary Nozzle was unavailable.). The audits were conducted according to the protocol recommended by the Irrigation Association (2004). The systems were first inspected and any obvious deficiencies (such as missing nozzles, broken pipes, leaking fittings) were corrected. A catch-can test was performed to determine the uniformity achieved by the fixed spray heads. Then the irrigation systems were converted to the MSMTR sprinklers, and a second catch-can test was conducted. A total of 51 audits were conducted, as summarized in table 2. A consequence of this procedure is that existing spray heads were of various unknown ages, where as the MSMTR sprinklers that replaced them were new.

For 35 of the zones audited, the head location, spacing, and other operating conditions were the same during each pair of catch-can tests, except for the sprinklers used. The first audit, sprinkler replacement, and the second audit were all conducted on the same day. The number and location of the catch-cans for the audits before and after sprinkler conversion were the same.

For 16 of the zones, audits were conducted under a program whose overall objectives went beyond the direct comparison of fixed spray and MSMTR sprinklers. Under this program, conversion allowed changes beyond just the replacement of sprinklers. In some cases, one or more of the pre-existing spray head locations were eliminated: fewer MSMTR sprinklers were used to cover the same area previously irrigated by a greater number of spray heads. In seven of these zones, flexible pipe was used to adjust the location of some of the remaining head locations. For none of these 16 zones was the spatial density of head locations increased for the MSMTR sprinklers. Audits conducted before and after the conversions for these zones were not conducted on the same day, and employed numbers and locations of catch-cans that may not have been the same.

Because of these differences in data collection protocols, the data collected was subdivided into two subsets for later analysis and comparison. Audit data from the 16 zones where elimination and repositioning of some head locations was allowed was designated Data Subset 1. Audit data from the 35 zones where before and after head location, catch-can number, and location were identical was designated Data Subset 2.

Calculation of distribution uniformities may involve catch-can data subgroups containing the lowest 25% (low quarter), 30%, 40%, or 50% (low half) of all catch-can values. The number of catch-can values from typical audits may not be evenly divisible into subgroups of the requisite sizes. Therefore, a linear interpolation scheme on the original sorted catch-can data was used to produce an equivalent set of 100 catch-can values. Figure 3 illustrates this process for the audit of zone j-1f, with MSMTR sprinklers installed. Twenty-one catch-can values were actually collected during the field audit. The interpolation process produced an equivalent set of 100 catch-can values.

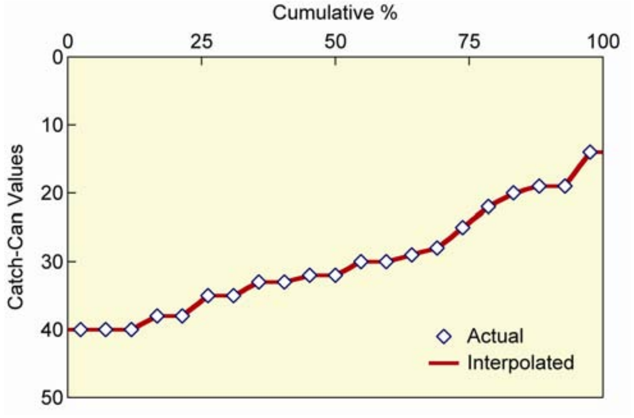

Figure 3. Comparison of actual and interpolated catch-can values for the audit of zone j-1f with MSMTR sprinklers.

PERFORMANCE MEASURES

DISTRIBUTION UNIFORMITY

The concepts of distribution uniformity (DU) and low quarter distribution uniformity (DU_{LQ}), previously introduced, can be generalized. DU_{LQ} is the most frequently used version of DU, although others are possible. When the critical least watered area is taken as the low 50% (the *low half*), then DU becomes DU_{LH}. Kissinger and Solomon (2005) introduced a generalized notation for distribution uniformity:

$$DU_{LXX} = \frac{V_{LXX}}{V_{avg}} \tag{1}$$

where V_{LXX} is the average of the low XX%, and V_{avg} is the average overall. In this notation, DU_{LQ} = DUL25 and DU_{LH} = DUL50. It will be useful in some of the discussions that follow to use equation 1 to define DU_{L30} and DU_{L40}, based on the low 30% and 40%, respectively.

QUALITY OF COVERAGE

The Irrigation Association (2005, tables 1-8, page 1-22) uses DU_{LQ} to classify the quality of coverage (as related to irrigation water usage) in a fixed spray zone (table 3). Note that this is a different quality rating scheme than the one cited by Baum et al. (2002, 2003a, 2003b, 2005) and Dukes et al. (2004), which is a quality scale intended for application to systems as a whole, which may include both spray and rotor

Table 3. Quality rating scale for fixed spray zones (Irrigation Association, 2005).

Fixed Spray Zone DULQ	Quality Rating
0.75 and above	Excellent
0.65 - 0.74	Very Good
0.55 - 0.64	Good
0.50 - 0.54	Fair
0.40 - 0.49	Poor

zones. The quality scale shown in table 3 is intended for application to individual spray zones.

RUN TIME MULTIPLIER

The Irrigation Association (2005) recommends that DU_{LH} be used for irrigation scheduling. DU_{LH} is used as an efficiency term to compute a run time multiplier (RTM):

$$RTM = \frac{1}{DU_{LH}} \tag{2}$$

If T is the theoretical (i.e., assuming a perfectly uniform application of water) run time needed for the irrigation system to apply the required amount of water, then T × RTM is the actual irrigation run time that will be needed to overcome the effects of nonuniformity. Lower values of RTM (corresponding to higher values of DU_{LH}) are preferred.

The practical meaning of the Irrigation Association's recommendation and the RTM computation is that irrigation times should be adjusted so that the average application amount in the low 50% (the low half average) is equal to the required amount. If the low half average is substantially lower than the overall average (poor uniformity, low DU_{LH}), considerable over watering may be needed to make the low half average equal the required amount. Better uniformity (higher DU_{LH}) means that the overall average is closer to the low half average, so less water is needed to make the low half average equal the required amount.

The Irrigation Association's rationale for the recommendation to use LH (DU_{LH}, RTM_{LH}) rather than LQ (DU_{LQ}, RTM_{LQ}) for irrigation scheduling is that water may move horizontally through the thatch or soil, and the uniformity of soil moisture may be higher than indicated by catch-can tests (Mecham, 2001): "An improved [compared to DU_{LQ}] representation of soil moisture uniformity for scheduling purposes is the *lower-half* distribution uniformity [as computed from catch-can values]" (Irrigation Association, 2005).

This approach to setting irrigation times has proved reasonable for systems with adequate uniformity. However, for systems with low uniformities, setting irrigation times with RTM_{LH} may result in some visual signs of stress in the turf or landscape. In such cases, it is recommended to correct the problems that cause the low uniformity, instead of over-watering in an attempt to deliver adequate water to those locations receiving the least amount of water. From the water conservation standpoint, this is certainly the preferred approach.

These recommendations notwithstanding, some irrigation managers may simply increase run times to apply more water in an attempt to alleviate the dry spots and turf areas of poor visual quality. Increasing application amounts and run times beyond the values set by equation 2 is equivalent to choosing a DU based on an area smaller than LH as the efficiency term in equation 2. Managers over-watering to eliminate dry spots probably do not think in terms of basing RTM on DU_{LXX}, but this is a numerically equivalent and convenient way to quantify their actions. Like DU, RTM can be generalized, depending on which DU value is used as the efficiency term:

$$RTM_{LXX} = \frac{1}{DU_{LXX}} \tag{3}$$

where RTM_{LXX} indicates that the run time multiplier is based on DU_{LXX}. Run times so determined will match the average application in the low XX% to the required irrigation amount.

Anecdotal evidence suggests that when irrigation run times are based on catch-can DU_{LQ}, the run times are usually more than what is already set on the controller. Further, in these cases the owners were reasonably happy with the visual appearance of the turf (Mecham, 2005). Therefore, calculating run times and water application amounts using RTM_{LQ} probably over-estimates the application amounts of managers over-watering to eliminate dry areas. Based on these observations, Kissinger and Solomon (2005) used RTM_{L30} to characterize the management regime of turf managers over-watering to eliminate dry areas. This is equivalent to adjusting run times so that the low 30% average is equal to the required amount.

Setting run times using RTM_{LH} is the recommended water management regime. Setting run times using RTM_{L30} characterizes the practice of over-watering to eliminate dry spots. These two choices span the range of anticipated water management practices. A mid-range water management regime might use RTML40 to set irrigation run times.

WATER CONSERVATION POTENTIAL

DU and RTM are performance measures that can be applied to a particular zone within a landscape irrigation system. Water conservation potential, however, is a property associated with a *change* in the distribution uniformity or management regime of an irrigation zone. If the water conservation potential is positive, the change would be regarded as an improvement. Improve the distribution uniformity, and from equation 2 the RTM decreases, so less water is required to meet the irrigation requirement. Changing the water management regime so that irrigation times are set using RTM_{LH} instead of RTM_{L30} will also require less water. To measure the water conservation potential of the improvement, then, one must calculate how much less water is needed after the improvement than before to meet the irrigation requirement.

The total water volume applied to meet a given irrigation requirement depends on the distribution uniformity of the zone and the management regime used. This volume is proportional to RTM_{LXX}. Therefore, the water conservation potential due to an improvement is proportional to the difference between pre- and post-improvement RTM values: $RTM_{LBB,b}$ and $RTM_{LAA,a}$. The subscripts LBB,b and LAA,a denote the size of the critical, least watered area used to determine DU and set the RTM for the cases *before* and *after* the improvement, respectively.

Note that the BB in LBB,b isn't necessarily the same as the AA in LAA,a. For example, consider the case of an existing system with poor uniformity where the manager has increased run times to avoid dry spots and turf areas of poor visual quality, setting irrigation times using RTM_{L30} (LBB,b = L30,b). After changing sprinklers to a model with better coverage, the uniformity is high enough that irrigation times may be set using RTM_{LH} (LAA,a = LH,a). Water conservation potential in this case includes both (i) the savings due to the improved uniformity, and (ii) the savings due to an improved water management regime (i.e., irrigation times set with $RTM_{LH,a}$ instead of $RTM_{L30,b}$).

The water conservation potential due to an improvement, expressed as a percentage of the pre-improvement water application, can be calculated:

Water Conservation Potential =

$$100\% \times \left[\frac{(RTM_{LBB,b}) - (RTM_{LAA,a})}{(RTM_{LBB,b})} \right] \tag{4}$$

Substituting from equation 3 into equation 4 and simplifying leads to:

Water Conservation Potential =

$$100\% \times \left[1 - \frac{DU_{LBB,b}}{DU_{LAA,a}} \right] \tag{5}$$

In the example previously given, when the manager set irrigation times using RTM_{L30} before the conversion, and using RTM_{LH} after the conversion, the calculation of water conservation potential would be:

Water Conservation Potential =

$$100\% \times \left[1 - \frac{DU_{L30,b}}{DU_{LH,a}} \right] \tag{6}$$

DEFICIT AVOIDED

The word *deficit* applies to a particular location when the water application amount at that location does not fully meet the irrigation requirement. It is impractical to water long enough to prevent any deficit on all portions of the irrigated area. Even managers watering to eliminate dry spots do not really eliminate all deficits – they only attempt to reduce deficits to the point where the visual appearance of the turf is acceptable. Setting run times with RTM_{L30} matches the average in the low 30% to the required irrigation amount. Still, roughly half of the L30 area will receive less water than the L30 average, and so will be in deficit.

The total amount of the deficit can be calculated:

$$\text{Deficit} = \sum_{i \in D} a_i (R - A_i) \tag{7}$$

where

Deficit = total deficit remaining after an irrigation (volume)

i = index for each individual location

D = set of all i for which $(R - A_i) > 0$

a_i = area associated with location i (area)

R = requirement at time of irrigation (depth)

A_i = applied amount at location i (depth)

If changes in uniformity or management regime are made that reduce the deficit, the improvement can be quantified by calculating the deficit avoided, expressed as a percentage of the pre-existing deficit:

Deficit Avoided =

$$100\% \times \left[\frac{\text{Deficit}_{\text{Before}} - \text{Deficit}_{\text{After}}}{\text{Deficit}_{\text{Before}}} \right] = \tag{8}$$

$$100\% \times \left[1 - \frac{\text{Deficit}_{\text{After}}}{\text{Deficit}_{\text{Before}}} \right]$$

WATER DESTINATION AND WATER CONSERVATION DIAGRAMS

Solomon and Kissinger (2005) provide a detailed discussion of water destination diagrams and water conservation diagrams, and propose their use to illustrate changes in uniformity or management regime and the resulting changes in water application volumes. Water destination diagrams show catch-can values, sorted from large to small values, plotted vertically down (to represent water that has infiltrated into the soil). The horizontal scale represents the area being irrigated (fig. 4). Water application curves representing systems with good uniformity are relatively flat, while curves for systems with poor uniformity are steeper.

When water application amounts are compared to the irrigation requirement, the water destination diagram readily identifies water applied in excess of the requirement, and deficits where the water applied is less than the requirement (fig 4).

Water conservation diagrams show a pair of water destination diagrams, for circumstances before and after an improvement, plotted on the same chart. In this case, the diagram is useful for highlighting changes in the water application amount and deficit due to the improvement.

RESULTS

UNIFORMITY (DU_{LQ}) AND RUN TIME MULTIPLIER (RTM_{LH})

Results for the 51 individual zones audited, both before and after the conversion from fixed spray to MSMTR sprinklers, are summarized in table 4.

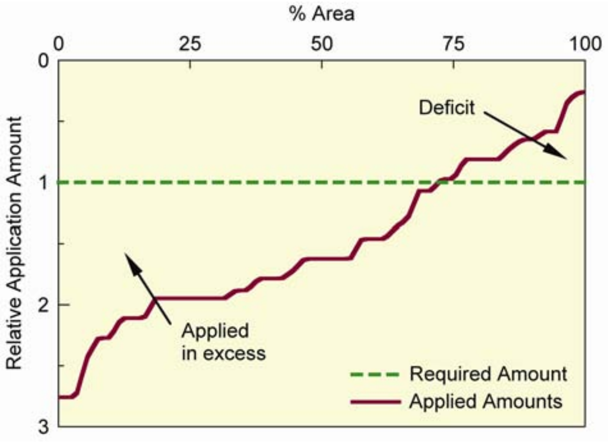

Figure 4. Sample water destination diagram.

Table 4. Changes in DU_{LQ} due to conversion to MSMTR sprinklers for the two data subsets using different audit protocols.

	Data Subset 1	Data Subset 2
Auditors	Farrens	Kissinger, Borneman
Elimination/repositioning of head locations allowed?	Yes	No
Before/after audits conducted on the same day?	No	Yes
Catch-can positions identical for before/ after audits?	No	Yes
Number of before/after audit pairs	16	35
Before conversion (fixed spray heads): Average DU_{LQ}	0.425	0.442
After conversion (MSMTR sprinklers): Average DU_{LQ}	0.596	0.704
Improvement due to conversion: Average Δ DU_{LQ} [95% confidence interval]	0.170[a] [0.136, 0.205]	0.262[b] [0.226, 0.298]

[a] [b] The differing increase in DU_{LQ} between Data Subsets 1 and 2 is significant (p = 0.003).

DU_{LQ} increased after conversion to the MSMTR sprinklers by an average of 0.170 for data subset 1, where elimination and repositioning of head locations was allowed during conversion, and 0.262 for data subset 2, where head numbers and locations were identical before and after sprinkler conversion (table 3). This difference is significant (p = 0.003). Elimination of head locations in the zones for data subset 1 resulted in wider spacings, on average, for the MSMTR sprinklers than for the fixed sprays they replaced.

Data from the two subsets were analyzed separately. The results from subset 1 (not illustrated here) followed the same general trends as results from subset 2. Elimination/repositioning of head locations for the zones of subset 1 makes each zone a special case, so none of those results are transferable. Therefore the results of data subset 1 were taken only as qualitative support for the quantitative results for data subset 2, and subsequent portions of this article will present results only from the audits of the 35 zones for data subset 2.

In general, the uniformity for the 35 zones in data subset 2 using fixed spray heads was not good. Only seven of the zones rated better than *Poor* (based on the Irrigation Association's quality rating scale for fixed spray zones, table 3), and 11 did not even achieve the *Poor* rating (fig. 5). The average pre-conversion DU_{LQ} was 0.44, lower than the average reported by Mecham (2004) for residential fixed spray head systems by 0.08. Replacing the fixed sprays in these zones with MSMTR sprinklers raised DU_{LQ} to an average of 0.70. The average increase in DU_{LQ} was 0.26 (95% CI [0.226, 0.298]). Thirty-four of the 35 zones achieved post-conversion DU_{LQ} quality ratings (table 3) of *Fair* or better, and 15 zones rated *Excellent*. The results for RTM_{LH} showed similar trends (fig. 6). Conversion from fixed spray to MSMTR reduced average RTM_{LH} by 0.385 [95% CI (0.286, 0.483)].

Water Conservation Potential and Deficit Avoided

The water conservation potential due to an increase in DU_{LQ} depends on the extent of the increase and on the pre-conversion management regime – i.e., on the pre-conversion choice of BB in $RTM_{LBB,b}$. Although RTM_{LH} is recommended (Irrigation Association, 2005), some managers may choose the increased run times based on RTM_{L30}, particularly if they must contend with low uniformity. The consequences of this choice are illustrated in figure 7, which is based on the audit of zone j-23k with fixed spray heads. DU_{LQ} for this zone was 0.44, equal to the average DU_{LQ} for the 35 zones audited when using fixed sprays.

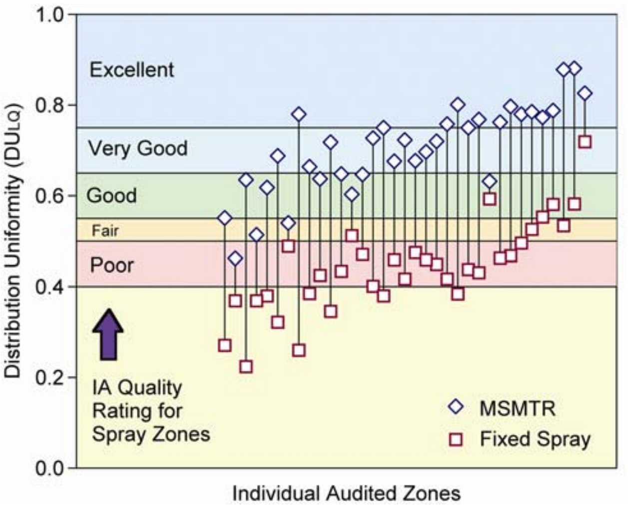

Figure 5. Change in DU_{LQ} after conversion from fixed spray to MSMTR sprinklers for 35 individual audited zones.

Using RTM_{L30} instead of RTM_{LH} increases run time. This change does reduce the deficit. However, most of this decrease comes in those areas that were just slightly under-watered, and the maximum deficit is still substantial. Considerable additional water (42% more in this case) is required to achieve this modest improvement.

The conversion of zone j-23k from fixed spray heads to MSMTR sprinklers achieved water conservation potential of 22% and 44% of the pre-conversion application with pre-conversion run times set by RTM_{LH} and RTM_{L30} respectively. Similarly, 73% and 67%, respectively, of the pre-conversion deficit were avoided (figs. 8 and 9).

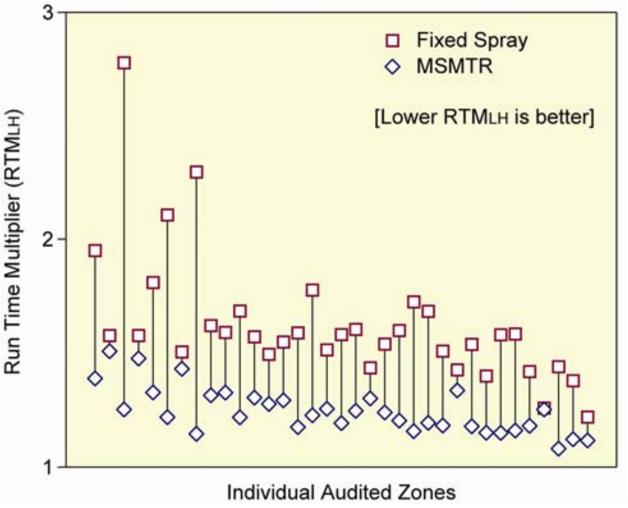

Figure 6. Change in RTM_{LH} after conversion from fixed spray to MSMTR sprinklers for 35 individual audited zones. In both figures 5 and 6, the pre- and post-conversion values for each zone are at the same location on the horizontal axis [i.e., symbols connected by a vertical line represent before (fixed spray, squares) and after (MSMTR, diamonds) results for the same zone].

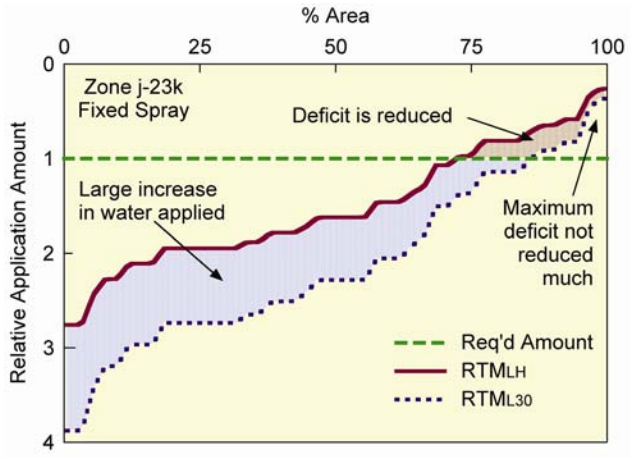

Figure 7. Water destination diagram for zone j-23k with fixed spray heads, showing application curves assuming irrigation run times are set based on RTM$_{LH}$ and RTM$_{L30}$.

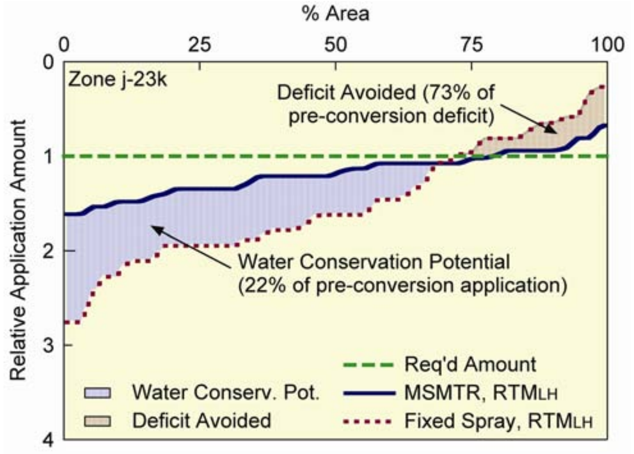

Figure 8. Water conservation diagram for zone j-23k showing water conservation potential and deficit avoided for conversion from fixed spray to MSMTR, assuming both pre- and post-conversion run times were set by RTM$_{LH}$.

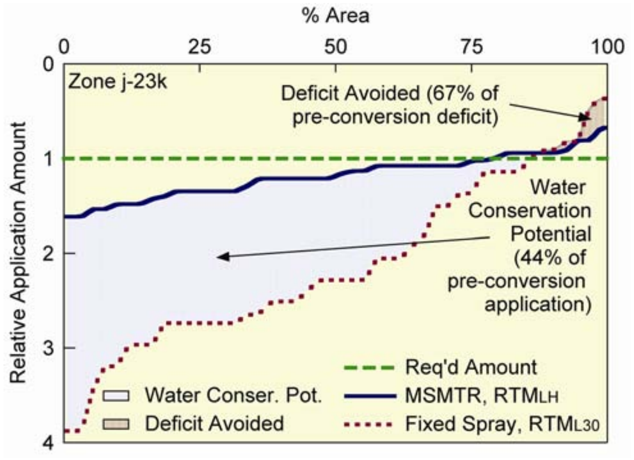

Figure 9. Water conservation diagram for zone j-23k showing water conservation potential and deficit avoided for conversion from fixed spray to MSMTR, assuming run times set by RTM$_{L30}$ and RTM$_{LH}$ (pre- and post-conversion RTMs, respectively).

Table 5. Water conservation potential and deficit avoided, as percentages of their pre-conversion values, due to conversion from fixed spray to MSMTR sprinklers, with post-conversion run times set using RTM$_{LH}$. N = 35.

Result	Pre-Conversion RTM	Average [95% C.I.]	Median
Water Conservation Potential (%)	RTM$_{LH}$	21.9 [17.9, 25.9]	21.7
	RTM$_{L40}$	30.7 [26.7, 34.7]	30.8
	RTM$_{L30}$	40.1 [36.2, 44.0]	38.8
Deficit Avoided (%)	RTM$_{LH}$	54.1 [46.9, 61.2]	56.9
	RTM$_{L40}$	41.1 [31.5, 50.8]	47.3
	RTM$_{L30}$	56.2 [46.8, 65.6]	62.6

Water conservation potential and deficit avoided results for the 35 zone audits in data subset 2 are summarized in table 5. Depending on pre-conversion choice of RTM, average water conservation potential ranged from 22% to 40%, and average deficit avoided ranged from 41% to 56% of their pre-conversion amounts.

Because water conservation potential and deficit avoided depend on pre-conversion conditions, they can vary as widely as pre-conversion uniformities (DU$_{LQ}$) and management regimes (RTM$_{LBB,b}$) vary. Figure 10 illustrates the range of water conservation potential achieved by conversion to MSMTR sprinklers for the 35 zones of data subset 2. The vertical axis plots the percent of the audits that achieved the indicated water conservation potential, or more. For example, looking at the left curve (circles) for pre-conversion run times set by RTM$_{LH}$, about half of the audits (corresponding to 50% on the vertical axis) showed that conversion to MSMTR sprinklers achieved an estimated conservation potential of 20% or more of the pre-conversion water amount (20% on the horizontal axis). The curve on the right (squares) for pre-conversion run times set by RTM$_{L30}$, shows greater water conservation potential: about half of the audits showed conversion to MSMTR sprinklers achieved an estimated water conservation potential of 40% or more of the pre-conversion water amount. Depending on pre-conversion uniformity and management, water conservation potential could be anywhere in the shaded zone between the curves.

A good single-point estimate for the water conservation potential of an MSMTR conversion is 31%. This is the median value for the estimated water conservation potential,

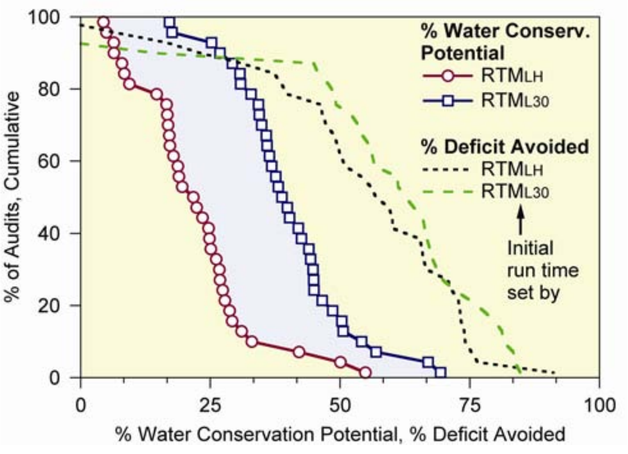

Figure 10. Water conservation potential and deficit avoided as per cents of the pre-conversion application amount and the pre-conversion deficit, respectively.

assuming a mid-range pre-conversion management regime where run times are set using RTM_{L40}.

Figure 10 also illustrates similar results for deficit avoided. Although the wide range in pre-conversion uniformities results in a correspondingly wide variation in deficit avoided, pre-conversion management does not strongly influence deficit avoided when expressed as a percent of the pre-conversion deficit. Figure 10 suggests that conversion to MSMTR sprinklers results in a similar percentage reduction in deficit for either pre-conversion management regime. In absolute terms, though, it is expected that pre-conversion management will affect deficit reduction. Setting pre-conversion run times using RTM_{L30} instead of RTM_{LH} would generally result in smaller deficits (fig. 7), so the conversion has less of a deficit (in absolute terms) to avoid.

DISCUSSION

The performance of the fixed spray systems for the 35 zones audited was low (average $DU_{LQ} = 0.44$, average IA quality rating = *Poor* , cf. table 3). No definitive reasons can be given for this performance, as the dual before/after audit procedure used in this study did not include diagnostic examinations of the systems audited. However, based on previous work by other investigators, it seems likely that the following may have contributed to the poor performance observed: lower than recommended operating pressure, uneven pressures throughout the zone, stretched or uneven spacing within the zone, sprinklers or nozzles with differing precipitation rates on the same valve, equipment-related issues such as specific distribution characteristics (brand) or the use of adjustable arc rather than fixed arc nozzles for part-circle patterns.

The performance of the same zones after conversion to MSMTR sprinklers improved significantly [$\Delta DU_{LQ} = 0.26$, 95% CI (0.226, 0.298), average $DU_{LQ} = 0.70$, average IA quality rating = *Very Good*, cf. table 3]. There are some specific characteristics of the MSMTR sprinkler which can explain this improvement in performance. An important difference is that the flow rate of MSMTR sprinklers is considerably lower than for comparable fixed spray heads (table 1). The multiple water streams, at multiple trajectories, rotating, require less water than fixed sprays to reach all portions of the area covered, and therefore can cover a zone at a lower discharge rate.

Because of this lower flow rate, when MSMTR sprinklers replace fixed sprays on an existing pipe and valve network, friction losses are reduced, leading to two types of changes. First, pressures at the various head locations within the zone will become more uniform. Second, reduced losses in the meter and supply line to the residence or landscape site, as well as pipes and valves upstream of the zone mean greater operating pressures at the sprinkler locations within the zone. Since lower than recommended operating pressure has been previously identified as a significant cause of lower DU_{LQ}, this second point could be important.

MSMTR sprinklers also have greater radii of throw than fixed spray sprinklers at comparable operating pressures (table 1). When replacing fixed spray heads at the same head locations, MSMTR sprinklers will provide greater relative overlap: the ratio of sprinkler radius to spacing distance will increase. Conversion will have made previously stretched spacings less so; previously marginal spacing choices may have become acceptable.

According to manufacturers' statements, the MSMTR sprinklers now commercially available maintain matched precipitation status when patterns are set or adjusted for different arcs or radii (these statements were not independently verified during this study) (Rain Bird, 2004; Walla Walla Sprinkler Company, 2006). If existing fixed spray zones contained sprinklers or nozzles with differing precipitation rates on the same valve, conversion to MSMTR sprinklers would have corrected this.

Because MSMTR sprinklers have lower flow rates than fixed spray heads, they also have lower precipitation rates and may require longer sprinkler run times to apply the water required by the turf or landscape. However MSMTR sprinklers also deliver higher DU_{LQ} values, which mean lower RTM. To determine the net result of these two counterbalancing effects, consider the following example calculation for a fixed spray zone that has been converted to MSMTR sprinklers. Values for DU_{LQ}, DU_{L30}, and DU_{LH} are taken equal to the average values obtained for each sprinkler type for the 35 zones audited in this study. Flow rate and radii are from table 1.

Fixed Spray Sprinklers	MSMTR Sprinklers (MP 2000 Rotator®)
Flow Rate/Head = 0.23 lps (3.65 gpm)	Flow Rate/Head = 0.08 lps (1.27 gpm)
Radius = 4.5 m (15 ft)	Radius = 5.2 m (17 ft)
Spacing = 4.5 m × 4.5 m (15 ft × 15 ft) square	Spacing = 4.5 m × 4.5 m (15 ft × 15 ft) square
Precipitation Rate = 41 mm/h (1.56 in./h)	Precipitation Rate = 14 mm/h (0.54 in./h)
$DU_{LQ} = 0.44$	$DU_{LQ} = 0.70$
$DU_{L30} = 0.48$	$DU_{L30} = 0.73$
$DU_{LH} = 0.63$	$DU_{LH} = 0.81$

In general, the run time needed to apply the R, the required amount (mm) is:

$$RunTime = \left(\frac{R}{PR}\right) \times RTM_{LXX} = \left(\frac{R}{PR \times DU_{LXX}}\right) \qquad (9)$$

where

Run Time = Run time needed to apply the required amount (h)

R = Required amount (mm)

PR = Precipitation Rate (mm/h)

The relative increase in run time for the MSMTR sprinklers over the run time needed for the fix spray heads is calculated by applying equation 9 to the case of the fixed spray heads before the conversion, and then to the case of the MSMTR sprinklers after the conversion, and then dividing the later by the former. After simplification, this results in

$$RunTime\,Ratio = \left(\frac{PR_{Spray} \times DU_{LBB,\,b}}{PR_{MSMTR} \times DU_{LAA,\,a}}\right) \qquad (10)$$

where Run Time Ratio is the relative run time for the MSMTR sprinklers compared to fixed sprays (dimensionless) and the subscripts Spray and MSMTR are used to specify their respective precipitation rates. Equation 10 assumes no runoff from the higher precipitation rate fixed spray heads.

For the sample calculation, it is further assumed that the uniformity with the MSMTR sprinklers is sufficiently high that irrigations may be scheduled according to DU_{LH}. As with estimation of water conservation potential, the calculation of Run Time Ratio depends on the pre-conversion management. If the irrigation manager was scheduling based on LH before conversion, then compute Run Time Ratio from equation 10 using $DU_{LH,b}$ = 0.63; if L30, then use $DU_{L30,b}$ = 0.48. The Run Time Ratios calculated are 2.28 and 1.74, respectively. Depending on pre-conversion management, and assuming no runoff from pre-conversion sprays, the MSMTR sprinklers may have to be run approximately 1.7 to 2.3 times as long as the fixed spray heads they replaced to apply the same net amount of water.

For a fixed uniformity, setting irrigation run times with RTM_{LH} will result in the greatest deficits: Using RTML40 or RTM_{L30} will reduce the deficits (but will increase the water applied). For a fixed RTM, increasing uniformity will decrease the deficits (and will decrease the water applied).

When both uniformity and management regime are changed, the effect on the deficit is less clear. Consider the example that led to the calculation of equation 6, where an existing system has poor uniformity and the manager has chosen to increase run times to avoid dry spots and turf areas of poor visual quality, setting irrigation times using RTM_{L30}. After changing sprinklers to a model with better uniformity, irrigation times may be set using RTM_{LH}. By itself, the improved uniformity would decrease the deficit. However, changing management regimes from RTM_{L30} to RTM_{LH} will actually expand the size of the area experiencing deficit. The end result on total deficit will depend on whether the uniformity change or the management regime change is the most significant. [Note: regardless of the net effect on total deficit, improved uniformity and the use of RTM_{LH} would conserve water].

This study has considered only those aspects of MSMTR performance and water conservation related to uniformity and the response of management to non-uniformity. The elimination of runoff and overspray (water sprayed outside the boundary of the area to be irrigated) could conserve additional water. Relevant sprinkler features would be lower precipitation rates, adjustable settings for arc of coverage and radius of throw, and the ability to maintain matched precipitation rates while making these adjustments. Some MSMTR sprinklers possess all the properties mentioned; other MSMTR sprinklers, and other turf/landscape spray heads, may lack one or more of these properties. The water conservation potential of these additional factors has not been evaluated.

CONCLUSIONS

Performance of fixed spray and MSMTR sprinklers under field conditions was accomplished through audits conducted before and after conversions from spray to MSMTR sprinklers for 51 individual zones at 29 sites in four states. These audits yielded 35 sets of before and after audit data collected under conditions where head locations, general operating conditions, and audit protocols were the same for both before and after audits.

Performance of existing zones with fixed spray heads was low: DU_{LQ} averaged 0.44, rated *Poor* according to the Irrigation Association's rating scale for individual spray zones. After conversion to MSMTR sprinklers, these same zones exhibited improved performance: DU_{LQ} increased by 0.26, to an average 0.70, rated *Very Good* on the Irrigation Association's rating scale. A similar performance differential was found for the Run Time Multiplier, as conversion from fixed sprays to MSMTR sprinklers reduced average RTM_{LH} by 0.39.

Water conservation diagrams were used to illustrate the estimation of water conservation potential and deficit avoided due to the conversion from fixed spray to MSMTR sprinklers and/or change in irrigation management regime, as quantified by the choice of RTM. RTMs based on the average of the low 30% or the average of the low half (low 50%) span the range of anticipated management practices.

The water conservation potential associated with a conversion from fixed spray to MSMTR sprinklers depends on the pre-conversion uniformity and irrigation management practice. Average water conservation potential ranged from 22% to 40% of the pre-conversion application amount, depending on pre-conversion choice of RTM. A good single-point estimate for the water conservation potential of an MSMTR conversion is 31% of the pre-conversion application (the median value assuming pre-conversion run times set with RTM_{L40}),

The deficit avoided that is associated with a conversion from fixed spray to MSMTR sprinklers also varies with pre-conversion uniformity and irrigation management practice, but the influence of pre-conversion management is not strong.

Because of their lower precipitation rates, MSMTR sprinklers may be expected to require longer run times than fixed spray heads to meet the same application requirement. The improved uniformity of the MSMTR sprinklers partially mitigates this. A sample calculation, assuming no runoff from the higher precipitation rate fixed sprays, suggests that after conversion to MSMTR sprinklers, the MSMTR systems may need to run 1.7 to 2.3 times as long as the fixed sprays used to run to deliver the same net application.

ACKNOWLEDGEMENTS

The authors would like to thank the following organizations and agencies for their support of this work: Cal Poly, Pomona, Calif.; City of Long Beach Water Department, Long Beach Calif.; City of Walla Walla, Wash.; Eastern Municipal Water District, Perris, Calif.; Inland Empire Utilities Agency, Chino, Calif.; San Diego County Water Authority, Kearney Mesa, Calif.; Walla Walla Community College; Walla Walla Sprinkler Company; Walla Walla Watershed Alliance; WWCC Water Management Program.

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