IRRIGATION AND DRAINAGE
Irrig. and Drain. (2015)
DOI: 10.1002/ird.1878

EMITTER UNIFORMITY AND APPLICATION EFFICIENCY FOR CENTRE- PIVOT IRRIGATION SYSTEMS[†]

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ABSTRACT

A significant portion of the intensively cultivated agricultural areas in the Southern Great Plains of the USA is located in the Texas High Plains. Agriculture in this region mainly depends on water from the vast underground Ogallala Aquifer. Due to excess withdrawal and a slow recharge process, groundwater levels are declining in many areas of the aquifer. Recently, regulations have been enacted in the Texas High Plains for restricting the amount of water pumped from the Ogallala Aquifer. In addition to pumping restrictions, conserving water by promoting irrigation systems with high application efficiency is also a priority. We investigated the emitted uniformity and application efficiency of 14 centre-pivot irrigation systems in the Texas High Plains. Application efficiencies were in the range of 60–70% for mid-elevation spray application (MESA) systems, 70–80% for low-elevation spray application (LESA) systems, and greater than 90% for low-energy precision application (LEPA) systems. Correction of the small number of defective emitters per system would not realize significant water savings. However, water savings could be realized by switching from MESA or LESA to LEPA, assuming the choice of crop allowed it.

KEY WORDS: irrigation auditing; emitter uniformity; application efficiency; mid-elevation spray application; low elevation spray application; low-energy precision application

Received 29 April 2014; Revised 29 July 2014; Accepted 29 July 2014

RÉSUMÉ

Une partie importante des zones agricoles cultivées de façon intensive dans les grandes plaines du Sud des États-Unis est située dans les Hautes Plaines du Texas. L'agriculture dans cette région dépend principalement de l'eau du vaste aquifère d'Ogallala. En raison de prélèvements excessifs et des processus de recharge lente, les niveaux d'eau sont en baisse dans de nombreux domaines de l'aquifère. Récemment, des règlements ont été adoptés dans les Hautes Plaine du Texas pour limiter la quantité d'eau pompée dans l'aquifère d'Ogallala. En plus des restrictions de pompage, les économies d'eau sont également une priorité, et les systèmes d'irrigation à haute efficacité sont promus. Nous avons étudié l'uniformité émise et l'efficacité de l'application de 14 systèmes d'irrigation à pivot central dans les Hautes Plaines de Texas. L'efficacité de l'application était de l'ordre de 60–70% pour les systèmes de pulvérisation de moyenne altitude (MESA), 70 à 80% pour les systèmes de pulvérisation de basse altitude (LESA), et plus de 90% pour les systèmes de précision à basse énergie (LEPA). La réfection des émetteurs défectueux par système ne permettrait pas des économies d'eau importantes, en raison de leur petit nombre. En revanche, les économies d'eau pourraient être réalisées par le passage de MESA, LESA ou LEPA, sous réserve que le choix des cultures le permette.

MOTS CLÉS: audit d'irrigation; uniformité d'émetteur; efficacité de l'application; pulvérisation moyenne altitude; pulvérisation faible altitude; pulvérisation de précision à faible énergie

INTRODUCTION

The Ogallala Aquifer is one of the world's largest underground freshwater aquifers, spanning across eight states (South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico and Texas) in the Great Plains of

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[†] Uniformité de l'émetteur et efficacité de l'application pour les systèmes d'irrigation à pivot central.

United States. Irrigation of crops in this region relies on water from this aquifer (Rajan *et al.*, 2010). With large-scale irrigated agriculture starting in the 1950s, the Ogallala Aquifer has experienced a continuous decline with extraction far exceeding recharge (Ryder, 1996; Nair *et al.*, 2013a). Although more efficient irrigation technologies have been introduced over the past 50 years, these developments have not slowed depletion of the aquifer, and it is being mined at an unsustainable rate. The available storage in the Texas portion of the Ogallala Aquifer (Texas High Plains) in 1990 was estimated to be approximately 497 billion cubic metres (BCM). This value had fallen to 437 BCM by 2004. This represents a decline in storage of approximately 12% over this 15-year period, or slightly less than 1% per year averaged over the aquifer. However, the decline has been much greater in many portions of the aquifer. At the current rate of extraction, it has been projected that the majority of the aquifer has a usable lifetime of less than 60 years before it is depleted to levels incapable of supporting irrigated agriculture.

The growing concern about the depletion of the Ogallala Aquifer has resulted in several proposals for ways to conserve it. In past years, underground water conservation districts enacted rules that sought to conserve groundwater through the regulation of the spacing of new wells. However, it became apparent that additional rules were needed to directly restrict the use of water from the aquifer. These rules have stemmed from nearly two decades of state legislation aimed at improving conservation measures for groundwater resources throughout Texas. The High Plains Underground Water Conservation District (HPUWCD) has enacted a ’50/50 rule’ in an effort to conserve water in the Ogallala Aquifer. The goal of this rule is to have a minimum of 50% saturated thickness of the Ogallala Aquifer still available after 50 years (HPUWCD, 2011; Wang and Nair, 2013).

In addition to reducing the overall application of irrigation water, another important way to conserve water would be by promoting irrigation systems with high application efficiency (Hoffman and Martin, 1993; Nair *et al.*, 2013b). The application efficiency of an irrigation system is related to its ability to place water in the root zone of the crop and depends upon its design (spray, drip, furrow, etc.) and its condition (Howell, 2003). Efficient application of irrigation water is essential in avoiding under- or over-application of water. In the Texas High Plains region, about 75% of the irrigated area are under centre-pivot irrigation (Colaizzi *et al.*, 2010). Centre-pivot irrigation systems can be equipped with different types of emitters. These include mid-elevation spray application (MESA), low-elevation spray application (LESA) and low-energy precision application (LEPA) systems (New and Fipps, 2000). MESA systems use spray emitters positioned at around 1 m above the ground or higher, and are popular for irrigating taller crops like corn. LESA systems have spray emitters generally located less than 1 m above the ground, and are popular for irrigating shorter crops like cotton. LEPA systems use emitters in contact with the surface that allow water to flow directly onto the soil. The application efficiencies of these systems are affected by their specific designs and, for systems in individual fields, their age and maintenance. Auditing the efficiency and effectiveness of these irrigation systems is essential in identifying specific problems and overall performance.

In 2005, the project called ’An Integrated Approach to Water Conservation for Agriculture in the Texas Southern High Plains’ was initiated through funding from the Texas Water Development Board (Rajan *et al.*, 2013). This 8-year project led to the establishment of the Texas Alliance for Water Conservation (TAWC) Demonstration Project, which involves around 30 producers’ fields in the Hale and Floyd counties of Texas (Rajan, 2007). The primary objective of TAWC was to identify cropping systems and practices in this region that use less irrigation water while maintaining farm profitability. The study described here was conducted in conjunction with TAWC in selected centre-pivot irrigated fields in the project. The overall objective of the study was to evaluate the characteristics of MESA, LESA and LEPA systems in terms of proper nozzle selection, emitter uniformity and application efficiency.

MATERIALS AND METHODS

Study area

Fourteen centre-pivot irrigated fields were identified for conducting standard irrigation audits in 2012 and 2013 in the Texas High Plains region. These fields were part of the TAWC project. The climate of the region is semi-arid with an average long-term precipitation of around 450 mm (Rajan *et al.*, 2013; Cui *et al.*, 2014). All fields were located in the vicinity of Lockney, Texas (34°7′30″ N, 101°26′31.2″ W, 1100 m elevation). The soil type is a Pullman clay loam (a fine, mixed, superactive, thermic Torrertic Paleustoll) with 0–1% slope. The number of fields in the study with LEPA, LESA and MESA were 7, 4 and 3, respectively. One of the audited fields (Field 31) had seven spans set up for LEPA, but also had one span set up for LESA. This was done as part of the TAWC project to compare the effect of the two irrigation methods on crop growth and yield. Characteristics of these fields are summarized in Table I.

Flow measurements

For all centre-pivot fields, direct measurements of emitter flow rate were taken for the entire centre-pivot system. Emitter flow rates were measured by placing the emitter in

Table I. Characteristics of the fields and irrigation systems in this study

TAWC field number	Irrigation type	Field size (ha)	Maximum pumping rate ($m^3 min^{-1}$)[a]
03	MESA	20.19	1.70
04	LESA	20.14	1.89
06	LESA	20.09	1.89
07	LESA	21.29	1.89
09	MESA	38.93	3.40
10	LESA	28.43	3.02
14	LEPA	20.32	1.13
17	MESA	36.14	3.40
18[b]	LEPA	20.01	0.95
19	LEPA	19.71	1.51
20	LEPA	38.20	3.78
21	LEPA	20.07	1.89
22	LEPA	24.35	3.02
31	LEPA, LESA[c]	20.14	1.89

[a] Reported by the farmer to TAWC.

[b] Only outer three spans (6–8) were applying irrigation at time of audit. Results omitted from further analysis.

[c] One span (5) was set up as LESA for comparison with LEPA.

a plastic container and measuring the time it took for the water level to rise to a specified mark. The time was measured with a stopwatch. By knowing the volume of water in the portion of the container up to the mark, the flow rate of the emitter could be calculated. Two people were involved in making the measurements—one to handle the container and call out the starting and stopping times for filling to the mark, and the other to time the filling and record the measurements. It normally took approximately 2 h to measure all the emitters on an eight-span centre-pivot system (approximately 400 m) using this method. Larger fields took proportionately longer. Standard practice in many irrigation auditing efforts has been to determine the variation in emitter output along the length of the pivot system by catching the water at the soil surface below the emitters using catch cans. However, this is only an indirect estimate of emitter flow rate. The procedure used in this study provides more accurate direct measurements of emitter flow rates.

Emitter uniformity

Emitter flow rate data for the centre-pivot fields in Table I were graphed with the flow rate ($m^3 min^{-1}$) of each emitter plotted versus its respective position along the length of the centre pivot. This was done to evaluate two characteristics of the irrigation system: *proper nozzle selection* and *emitter uniformity*. Proper nozzle selection was evaluated by comparing the observed trend in emitter flow rates versus the theoretical trend in emitter flow rates determined from characteristics of the irrigation system. Theoretically, emitter flow rates should fall off linearly with distance from the centre of the pivot according to Equation (1) (*Water Application Solutions for Centre Pivot Irrigation*, Nelson Irrigation Corp., Walla Walla, Wash., 2008):

$$FR = \frac{2{*}\mathrm{Ls}{*}\mathrm{Qp}{*}\mathrm{Le}}{\mathrm{Lp}^2} \tag{1}$$

where FR is the flow rate ($m^3 min^{-1}$) for a given emitter, L_s is the distance (m) of the emitter from the centre of the pivot, Q_p is the total flow ($m^3 min^{-1}$) rate for the pivot, L_e is the distance between emitters (m) and L_p is the total length (m) of the pivot. This relationship assumes that the pivot is on level ground. To evaluate whether the system was properly nozzled, the relationship calculated using this equation was compared to the simple linear regression placed through the graphed flow rate data. In general, the two relationships (lines) should be about the same. A significant deviation, within the scatter of the individual data values, would indicate that all or a portion of the pivot system was not properly nozzled.

Emitter uniformity was evaluated by constructing confidence limits about the regression line and determining how many individual emitters had flow rates outside the confidence limits compared to how many individual emitters had flow rates within them. The ratio of these two numbers, expressed as a percentage, is an indicator of overall emitter uniformity for the irrigation system. The upper and lower confidence limits about the regression were established based on the standard deviation calculated for the flow rate data for each field. The upper confidence limit is equal to the regression plus two standard deviations. The lower confidence limit is equal to the regression minus two standard deviations. Points on the graphs lying above or below the pair of confidence limits can be considered as 'outliers' and represent flow rate values significantly different from the general trend, accounting for random measurement error. Results of evaluating nozzle selection and emitter uniformity were analysed between individual systems, and average values for the three main centre-pivot irrigation systems in this study (MESA, LESA and LEPA) were compared to provide cross-system evaluations.

SYSTEM APPLICATION EFFICIENCY

Application efficiency is a function of how much of the irrigation water emitted by the system makes it into and remains within the root zone so that it is available for uptake by crop plants. Application efficiency (E_a) can be calculated as follows:

$$E_a = \left[\mathrm{W_i} - W_a - W_s - W_p\right] / W_i \tag{2}$$

where W_i is the water put out by the emitters, c the water lost in the air before it reaches the soil surface, W_s the water lost through evaporation from the soil surface and W_p the water lost through deep percolation from the soil profile. Each of the terms on the right-hand side of Equation (2) can be expressed as depth of water (ha m). E_a is often expressed as a percentage. In traditional irrigation system audits, water is collected at ground level below the emitters of a centre pivot using devices such as 'catch cans'. Such devices actually measure $W_i - W_a$ and thus provide only an estimate of W_i. For this reason, W_i was measured directly in this project using devices such as plastic containers placed to catch the water as it exited an emitter. To evaluate E_a for the various irrigation types observed in this project, special sets of measurements were performed in selected fields (Fields 17 and 31). Results of these measurements, along with assumptions drawn from the literature, were used to evaluate the terms in Equation (2) and thereby provide estimates of E_a.

The W_a term has two components: one related to the evaporation of water as it falls through the air (W_{air}) and the other related to the water intercepted by the crop canopy and eventually evaporated from the vegetation surfaces (W_{plant}), so that

$$W_a = W_{air} + W_{plant} \tag{3}$$

One of the audited fields (Field 31) had seven spans set up for LEPA, but also had one span set up for LESA. Catch trays were used to measure the amount of irrigation water reaching the soil surface under each system. These trays were 0.8 m long, 0.36 m wide and 0.15 m deep. Trays were used instead of catch cans because the low height of the emitters above the soil surface (nominally around 0.30 m) made the catch cans ineffective in catching the water put out by the emitters. In Field 31, one set of trays was placed to catch water from the LEPA emitters (span 4), while another set of trays was placed to catch water from the LESA emitters (span 5). The trays were placed so that their long dimension spanned the distance between adjacent rows of cotton. The cotton in this field was planted in 1 m rows, so the trays covered most of the area between the rows. At the time of the measurements, the cotton canopy in the fields had a ground cover (GC) of 45% and a leaf area index (LAI) of approximately 1.42. Depth of water in the trays was measured after the irrigation system passed over their location. Values from trays between the same pair of rows were averaged.

Theoretically, we would expect that W_{plant} should increase as the density of the plant canopy increases, i.e. more plant canopy intercepts more water. Numerically, we can express this as

$$W_{plant}/W_i = 1 - e^{-k(LAI)} \tag{4}$$

In this relationship, k is a parameter that describes how effective the plant canopy is at intercepting the water coming from the irrigation system emitters. The value of k can be evaluated from field data. Using the observations from Field 31, k =0.081.

Another set of measurements were taken to evaluate the other component of W_a (W_{air}) in Equation (3). One would expect that the magnitude of W_a would increase as the height of the emitter increased, i.e. more falling distance would result in more evaporation of the falling water. A set of measurements was taken involving the MESA system located at TAWC Field 17. This involved setting out an array of catch trays at a location within the outermost span of the irrigation system to collect water at ground level as the pivot moved over. These measurements were taken on the same day as the audit for this field. At the time of these measurements, the crop (corn) had just recently emerged so that it was shorter than the sides of the catch trays. Thus, the crop did not intercept water falling from the emitters to the trays. For this MESA system, the emitters were approximately 1.2 m above the ground. Following the passage of the irrigation system, the depth of the water in the trays was measured. Based on the speed of the pivot and the distance from the centre of the pivot to the spot where the trays were placed, the equivalent application amount could be calculated.

For irrigation systems that apply water to the soil surface (MESA, LESA and LEPA), a significant amount of water can be lost through evaporation from the soil surface (W_s in Equation (2)). Following an irrigation, water is predominantly lost through evaporation from the wet soil surface. This is called 'Phase I' evaporation and occurs at the rate determined by potential evapotranspiration (PET). Once the soil surface dries, water is lost from the soil by 'Phase II' evaporation. This is controlled by the diffusion of water vapour through the soil and is generally much less than Phase I evaporation. Previous studies in the TAWC project involving microlysimeter measurements have shown that Phase II evaporation is of the order of 0.5 mm day^{-1} or less. While Phase I evaporation proceeds at the rate determined by PET, the total amount of moisture lost through Phase I evaporation is a function of soil type. The 'upper limit for Phase I soil evaporation' (U) has been evaluated for a variety of soils by Ritchie (1972). For the types of soil in most TAWC fields, U is approximately 8.75 mm. This value has been verified by eddy covariance measurements of soil evaporation conducted in a bare soil field (TAWC Field 29) during the 2013 growing season. For a given irrigation event, U could also be limited by the amount of water applied (i.e. $U \leq W_i - W_a$), but most irrigations will be substantially greater than U.

In addition to evaluating U, Ritchie showed that soil evaporation is strongly affected by the amount of vegetation covering the soil surface. The more the plant canopy covers the soil surface, the less solar energy reaches the soil surface to evaporate water from it. Thus, W_s should decrease as crop ground cover increases. In fact, the soil surface under full canopy cover can remain wet for a long time after an irrigation or rainfall event due to reduced Phase I evaporation. However, another factor also influences W_s—the fraction of the total soil surface wet by irrigation. Soil evaporation for MESA and LESA irrigation systems should be greater than soil evaporation for LEPA systems, since the latter typically wet only a portion of the soil surface. Many LEPA systems in the TAWC project are set up to apply water to every other row, so they would wet only half the soil surface area that is wet by MESA or LESA systems. The combined effects of crop ground cover and irrigation type on the W_s term in Equation (2) can be quantified as follows:

$$W_s = U(1 - \mathrm{GC})(F_w) \tag{5}$$

where GC is the ground cover of the crop expressed as a fraction ($0 \leq \mathrm{GC} \leq 1$) and F_w is the fraction of the total soil surface wet by the irrigation system ($0 \leq F_w \leq 1$).

A number of fields in the TAWC project are equipped with deep soil moisture monitoring sensors (either AquaSpy or John Deere). These sensor systems are capable of measuring soil moisture in the soil profile at depths down to 1.2 m, a depth that is typically deeper than the rooting zone for crops in this region. Review of data from these sensor systems indicated no appreciable loss of soil moisture through deep percolation during the 2012 and 2013 growing seasons. Thus, for typical fields in the TAWC project, we can conclude that $W_p \approx 0$.

Equations (2–5 provide the basis for estimating the application efficiency E_a for the various irrigation systems in the TAWC project.

RESULTS AND DISCUSSION

For the sample of centre-pivot fields observed in this project, the linear regressions through the emitter flow rate data tended to be close to the predicted trends in emitter flow rates calculated using Equation (1), suggesting that the selection of nozzles was appropriate for the system (Figures 1(a)–1(m)).

Uniformity for fields was determined by how many emitters had flow rates between the upper and lower limits in Figures 1(a)–1(m), compared to the total number of emitters on the irrigation system (Table II). It should be recognized that all of the emitter-to-emitter variability in the figures is not associated with uniformity—some of the variation is due to random measurement error. All values of uniformity were greater than 90%, with the average uniformity being 96.7%. In Fields 14 and 19, the producers had every other emitter turned off at the times of the audits. These intentionally skipped emitters were not included in the calculations of uniformity. In the field, emitters with flow rates above or below the upper and lower limits were invariably damaged or obviously missing parts. These could be easily repaired or replaced. However, the overall high uniformity values suggest that the effects of non-uniform emitters on the crop were probably small.

Values of total flow (Q_p) for each field were determined by adding all the individual emitter flow rates for an irrigation system (Table II). They can be compared to the maximum pumping rates reported for each field in Table I. Some of the Q_p values are considerably less than the reported maximum pumping rates, which is indicative of the use of deficit irrigation. In a number of cases (Figures 1 (b), 1(c), 1(f), 1(h), 1(k), 1(l) and 1(m)), flow rates for emitters in the span closest to the centre of the pivot were relatively constant and did not decrease to approximately zero at the pivot centre as would be predicted by Equation (1). From a practical standpoint, flow rates near the pivot centre are already low, so adjusting nozzles in this range to make the flow rate go to zero at the pivot centre (as predicted by Equation (1)) would be an unnecessary detail. In all cases, the predicted line (Equation (1)) lies between the upper and lower confidence limits for the regression in each figure.

Results from Field 31 showed that, of the water emitted by the LEPA emitters, approximately 0.042 m reached the soil surface. For the LESA emitters, only around 0.038 m reached the soil surface. With the LEPA emitters, water was applied directly to the soil surface between adjacent rows. Thus, there should have been little loss of water between the emitter and the soil surface. The LESA emitters sprayed water out horizontally, with a large portion being intercepted by the plant canopy. The difference between the values for the two systems was likely the result of the water intercepted by the plant canopy (W_{plant}). Water from the wet leaves in the canopy could later evaporate without reaching the soil surface, resulting in a lower irrigation application efficiency for the LESA portion of the system as compared to the LEPA portion. For the MESA system (Field 17), the average depth of water in the trays was 0.0404 m, with a standard deviation of 0.0007 m. From the audit data, the flow rates for the emitters passing over the trays were determined. The average flow rate was $0.012\,\mathrm{m^3\,min^{-1}}$. The application amount estimated was 0.0404 m, which is equal to the amount caught in the trays. Based on these findings, it was concluded that there was no appreciable evaporation of water falling from the emitters to the ground for this MESA system. This system is typical of MESA systems in the TAWC project. Results for LESA systems would be expected to be similar, since the height of emitters for LESA systems was less than that for MESA systems. Some studies have reported large losses of water due to evaporation (up to 40%), but these have involved large 'rain gun' type sprinkler systems in arid climates such

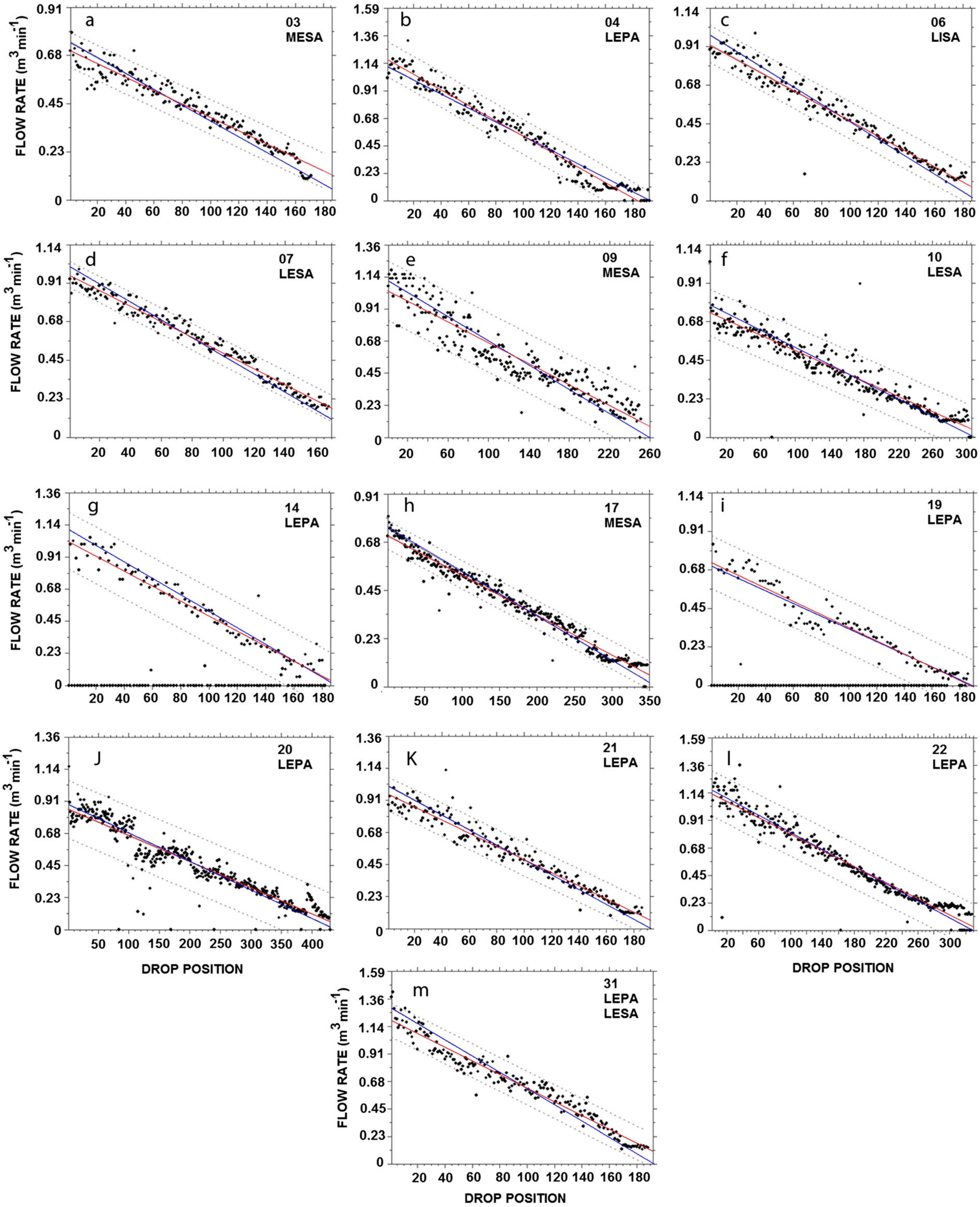

Figure 1. Trend in emitter flow rates for fields audited in the study. The graphs shows emitter flow rate plotted versus drop position from outside edge of the pivot. In each graph, the solid red line represents the simple linear regression through the distribution of points in the graph. The pair of dashed lines represents the upper and lower confidence limits about the regression. The solid black line represents the solution of Equation (1) for the particular field. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

as the Central Valley of California. For MESA and LESA systems in the TAWC project, we can conclude that $W_{\mathrm{air}} \approx 0$. This does not mean that W_{a} is the same for MESA and LESA systems. MESA irrigation systems are often used for tall crops such as corn, while LESA systems are used for shorter crops like cotton and grain sorghum. Corn typically

Table II. Total flow (Q_p) and emitter uniformity for the centre-pivot fields in the project

Field	Q_p ($m^3\ min^{-1}$)	Uniformity (%)
03	1.24	95.9
04	1.77	96.4
06	1.55	98.4
07	1.59	97.0
09	2.40	96.8
10	1.99	97.4
14	0.87	95.6[a]
17	2.23	96.3
19	0.56	98.9[a]
20	3.23	96.7
21	1.62	96.8
22	3.17	97.6
31	2.05	95.7

[a] Intentionally skipped emitters were not included in the calculation of uniformity.

achieves a much greater LAI than the other crops. Under such circumstances, MESA systems will have greater W_{plant} terms in Equation (3), resulting in greater values of W_a and lower system application efficiencies. Under bare soil conditions, MESA and LESA systems should perform similarly.

Average application efficiency estimates using Equation (2) for the three centre-pivot irrigations are in the general range of 60–70% for MESA systems, 70–80% for LESA systems and greater than 90% for LEPA systems (Table III). These values are similar compared to estimates reported from other studies (Schneider and Howell, 1990; Tolk *et al*., 1995; Schneider, 2000; Johnson *et al*., 2000). Note that the application efficiency increased when the applied water increased from 0.025 to 0.05 m. This is because, when more water is applied, a greater fraction penetrates into the root zone and proportionally less is lost through Phase I evaporation (since U is a constant for a given soil type).

Table III. Summary of application efficiencies (E_a) for various centre-pivot irrigation systems

		E_a (%)			
Type	Irrigation amount (in)	Bare soil (GC =0)	Partial canopy[a] (GC =50%)	Full canopy[b] (GC =100%)	Average
MESA	1	65.0	61.0	61.6	62.5
	2	82.5	69.8	61.6	71.3
LESA	1	65.0	71.1	78.5	71.5
	2	82.5	79.9	78.5	80.3
LEPA	1	82.5	91.3	~ 100	91.3
	2	91.8	95.6	~ 100	95.8

[a] MESA: corn with LAI =3; LESA and LEPA: cotton or grain sorghum with LAI =1.5.
[b] MESA: corn with LAI =6; LESA and LEPA: cotton or grain sorghum with LAI =3.

The efficiency of an irrigation system, which is a measure of how well it supplies water to the root zone of the crop, is related to the situation in which it is used. The canopy interception term (W_{plant}) in Equation (3) can be very important. MESA systems are generally used with taller, denser crop canopies while LESA or LEPA systems are used with shorter, more open canopies. This is reflected in the assumptions used in creating Table III. If MESA and LESA systems were used over bare ground, they would likely supply about the same amount of water to the soil surface (unless perhaps under very windy conditions). This equality is lost when we consider the presence of the crop canopy and the interception of water associated with it. If a LESA system were used with a taller, denser canopy, its efficiency would be greater than that of a MESA system in the same situation, since the LESA system would wet a smaller portion of the canopy (the lower part near the ground). A LEPA system would not wet any of the canopy. However, LESA and LEPA systems are not normally used with taller, denser crop canopies like corn, where their movement through the canopy could cause considerable damage to the plants. There is a link between the irrigation system and the cropping system in which it is normally used. Thus, *in practice*, MESA systems should be less efficient in supplying water to the root zones of the crops normally used with them, as compared to LESA and LEPA systems and their associated crops. These results assume that the irrigation systems are well maintained without significant mechanical problems, such as leaking delivery pipes. They also assume that the ground in the field is approximately level. Use of high irrigation rates could reduce these values due to runoff from the field and deep percolation. In summary, one can rank the general application efficiencies of the various irrigation systems as follows:

As indicated by the comparison of irrigation systems in Table III, substantial annual water savings could be realized by switching from less efficient to more efficient irrigation systems, assuming the choice of crop allowed it. A producer who applies a certain amount of water using a less efficient irrigation system could potentially see an effective increase in water applied if a more efficient irrigation system had been used, simply because a larger percentage of the applied water makes it into the rooting zone (and is not lost to soil evaporation or evaporation from plant surfaces) if a more efficient system is used. So, switching to a more efficient irrigation system is like getting 'extra' water to apply to the crop, even though the basic irrigation rate stays the same (Table IV). These show the increase in water that would be available for use by the crop if the producer switched to a more efficient irrigation system, calculated based on the assumptions used in Table III. Results are presented for situations where the producer would be applying 0.25, 0.30, 0.35 and 0.40 m of water with their current system.

Table IV. Potential increase in water (m) available for use by the crop from 0.25 to 0.40 m irrigation if the producer switches from a less efficient system (left column) to a more efficient system

Switch to …	MESA	LESA	LEPA
Current system applying 0.25 m			
MESA	0	0.0337	0.0997
LESA	–	0	0.0582
LEPA	–	–	0
Current system applying 0.30 m			
MESA	0	0.0405	0.1197
LESA	–	0	0.0700
LEPA	–	–	0
Current system applying 0.35 m			
MESA	0	0.0472	0.1397
LESA	–	0	0.0812
LEPA	–	–	0
Current system applying 0.40 m			
MESA	0	0.0540	0.1595
LESA	–	0	0.0932
LEPA	–	–	0

For example, Table IV suggests that if a producer were applying 0.25 m irrigation to a crop using a MESA system, switching to a LESA system would make an additional 0.0337 m of the original 0.25 m irrigation available for use by the crop. Switching to a LEPA system would make an additional 0.0997 m of the original 0.25 m irrigation available for use by the crop. The big difference between the values for switching to a LEPA system over switching to a LESA system reflect the marked increase in application efficiency between LESA and LEPA (Table III). These values are based on average application efficiencies for MESA, LESA and LEPA irrigation systems of 66.9, 75.9 and 93.6%, respectively. Actual values might vary from those presented in Table IV, but these results are useful in illustrating the relative gains to be made by switching from less efficient to more efficient irrigation systems.

A portion of the difference between the values for switching from MESA to LESA or LEPA involves the water intercepted by the crop canopy (W_{plant}). It might not be possible for some producers to realize the kinds of gains shown in Table IV without changing crops. As described earlier, MESA systems are typically used for irrigating tall, dense crops like corn. In this situation, it might not be feasible to switch from MESA to LESA or LEPA. From a practical point of view, the biggest gains in efficiency associated with these irrigation types would result from producers switching from LESA to LEPA. Such a switch would not involve a change in crop type. Switching from LESA to LEPA emitters is an easy task, so these improvements could easily be achieved. Other methods available to farmers in this region for potentially conserving irrigation water, such as irrigation scheduling, switching from furrow to centre-pivot irrigation, and switching cropping systems, have been described by Colaizzi *et al*. (2008).

CONCLUSIONS

For the irrigation systems audited in this project, the trends in emitter flow rates along the length of the pivot were generally close to the theoretical relationships described by Equation (1). Also, emitter uniformity for all systems was greater than 90%. No major deficiencies requiring correction were noted for the audited irrigation systems. Correction of the small number of defective emitters per system would not realize significant water savings. However, water savings could be realized by switching from MESA or LESA to LEPA, assuming the choice of crop allowed it. A producer who applies a certain amount of water using a less efficient irrigation system could potentially see an effective increase in water applied if a more efficient irrigation system had been used, simply because a larger percentage of the applied water makes it into the rooting zone (and is not lost to soil evaporation or evaporation from plant surfaces) if a more efficient system is used. So, switching to a more efficient irrigation system is like getting ’extra’ water to apply to the crop, even though the basic irrigation rate stays the same. Results presented in this article were derived from observations in the semi-arid Southern High Plains of the US. These results could be applicable to other semi-arid regions of the world that utilize similar cropping systems.

ACKNOWLEDGEMENTS

This study was supported by funding from the Texas Water Development Board (Contract TWDB # 1103581254).

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