

# Evaluating on-farm irrigation efficiency across the watershed: A case study of New Mexico's Lower Rio Grande Basin



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## ABSTRACT

Irrigation efficiency is a critical factor in irrigation water management. Irrigation efficiency is used in economic analysis when selecting an irrigation system design, and in irrigation management. It is also used in water rights adjudication and administration. On-farm irrigation efficiency is spatially and temporally variable and measuring irrigation efficiency is time consuming and costly. This paper describes a process to evaluate on-farm irrigation efficiency across the watershed using a combination of remote sensing and ground level measurements. On-farm irrigation efficiency was evaluated for three major crops in New Mexico's Lower Rio Grande Basin (LRG). The results of on-farm irrigation efficiency evaluation of 152 alfalfa fields, 189 pecan fields and 38 cotton fields showed that the average on-farm irrigation efficiency was 64%. However, on-farm irrigation efficiency values ranged from 11% to 95%. Accounting for delivery efficiency of 54%, the overall district efficiency was calculated as 35%. The study shows significant potential for improving irrigation efficiency in the LRG watershed; however, the inefficiency of the system is a major factor in recharging and sustaining the local aquifer. Significant improvement in on-farm and delivery efficiency can potentially change the hydrologic balance and result in depletion of the historically stable groundwater of the Mesilla Bolson.

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## 1. Introduction

Irrigation efficiency is a measure of the effectiveness of irrigation. It is a parameter which defines irrigation performance. Various definitions of irrigation efficiencies have been developed (Israelsen et al., 1944; Jensen, 1967; Bos, 1985; Jensen, 1993). Israelsen et al. (1944) defined water application efficiency as the "ratio of the amount of water that is stored by the irrigator in the soil root zone and ultimately consumed (transpired or evaporated or both) to the amount of water delivered to the farm." The American Society of Civil Engineers' (ASCE) on-farm irrigation committee (Kruse, 1978) has defined on-farm irrigation efficiency as the ratio of the volume of water that is taken up by the crop to the volume of irrigation water applied. The American Society of Agricultural and Biological Engineers has defined irrigation efficiency as the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied, expressed as a percent

(ASABE, 2007). The body of literature dealing with irrigation efficiency is vast and complex, with different concepts of irrigation efficiency continuing to emerge and be refined (Willardson et al., 1994; Seckler et al., 2003).

Understanding irrigation efficiency is fundamental to improving water management at the farm or watershed scale. In addition, the adjudication and administration of water rights in irrigated agriculture depends on understanding and management of irrigation efficiency. The Lower Rio Grande Valley (LRG) in Southern New Mexico is an agricultural watershed where crop production is dependent upon irrigation. Irrigation water is provided through annually allocated surface water from the Rio Grande managed by the Elephant Butte Irrigation District (EBID) and supplemental groundwater from privately owned irrigation wells. Surface irrigation is the predominant water application method in the area and is used on almost all fields; irrigation efficiency is a key parameter in local water management. Alfalfa, pecans, and cotton are the primary crops and are produced on about 80% of irrigated land in the area. In LRG surface irrigation, on-farm irrigation efficiency depends on various on-farm design and management factors such as soil type, field length, crop type, crop cultural practices, irrigation scheduling, and irrigation methods. Irrigation efficiency in such an environment is both spatially and temporally variable. The first step in improving water management in the LRG is to understand the

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nature and distribution of irrigation efficiency. In this study, remote sensing technology combined with irrigation and hydrologic information was used to evaluate the spatial and temporal variability of irrigation efficiency across the LRG watershed.

## 2. Methodology

### 2.1. Remote sensing model

The Regional ET Estimation Model (REEM) (Samani et al., 2006, 2007a, 2009) was used to calculate daily crop ET for various agricultural fields in the LRG in 2008. The REEM model has been previously validated by comparing daily, monthly and annual ET values estimated by the model with ET values measured with eddy covariance flux towers (Samani et al., 2006, 2007a, 2009). REEM is based on the surface energy balance similar to that presented by Bastiaanssen (1995) and Allen et al. (2007) with the latent heat flux (LE) determined as a residual of the surface energy equation:

$$LE = R_n - G - H \quad (1)$$

where LE is the latent heat flux,  $R_n$  is the net radiation flux at the surface,  $G$  is the soil heat flux and  $H$  is the sensible heat flux.

Daily net radiation over the crop canopy was calculated using methodology developed by Samani et al. (2007b) as:

$$R_n = R_{ni} \left( \frac{R_s}{R_{si}} \right) \left( \frac{T_a}{T_i} \right)^4 \quad (2)$$

where  $R_n$  is the daily net radiation in MJ/m<sup>2</sup>/day,  $R_{ni}$  is instantaneous net radiation (W/m<sup>2</sup>),  $R_s$  is daily short wave solar radiation (MJ/m<sup>2</sup>/day),  $R_{si}$  is the instantaneous short wave solar radiation (W/m<sup>2</sup>),  $T_a$  is average daily temperature in degrees Kelvin (K), and  $T_i$  is the instantaneous air temperature (K).

Instantaneous net radiation ( $R_{ni}$ ) was calculated by subtracting all outgoing radiant fluxes from all incoming radiant fluxes as described in the following equation:

$$R_{ni} = (1 - \alpha)R_{si} + RL \downarrow - RL \uparrow - (1 - \varepsilon_o)RL \downarrow \quad (3)$$

where  $RL \downarrow$  is instantaneous incoming long wave radiation (W/m<sup>2</sup>),  $RL \uparrow$  is instantaneous outgoing long wave radiation (W/m<sup>2</sup>),  $\alpha$  is surface albedo (dimensionless), and  $\varepsilon_o$  is surface emissivity (dimensionless).

The instantaneous sensible heat flux ( $H_i$ ) was calculated by combining the aerodynamic equation with Monin–Obukhov similarity theory. The aerodynamic equation:

$$H_i = \rho_a C_p \frac{dT}{r_{ah}} \quad (4)$$

where  $\rho_a$  is the air density (kg/m<sup>3</sup>),  $C_p$  is specific heat of air (1004 J/kg/K),  $dT$  is the difference between aerodynamic surface temperature and the air temperature (K),  $r_{ah}$  is the aerodynamic surface resistance.  $dT$  is calculated using a linear function described by Bastiaanssen (1995):

$$dT = aT_s + b \quad (5)$$

where  $a$  and  $b$  are calibration constants that are empirically determined on a daily basis by using reference extreme points on the ground. Calibration of Eq. (5) was accomplished using two points on the ground where  $dT$  values can be calculated from sensible heat ( $H_i$ ) fluxes using Eq. (4). In this study, two sensible heat values were used. One sensible heat value was measured over a pecan orchard using a one-propeller eddy covariance (OPEC) system. The orchard was a mature, well-watered pecan orchard which extended more than 5 km in the predominant wind direction as shown in Fig. 1 (latitude 32°13'31.57"N, longitude 106°45'23.57"W).

The other sensible heat value was estimated for a dry fallow field with no vegetation by setting instantaneous latent heat ( $LE_i$ ) equal

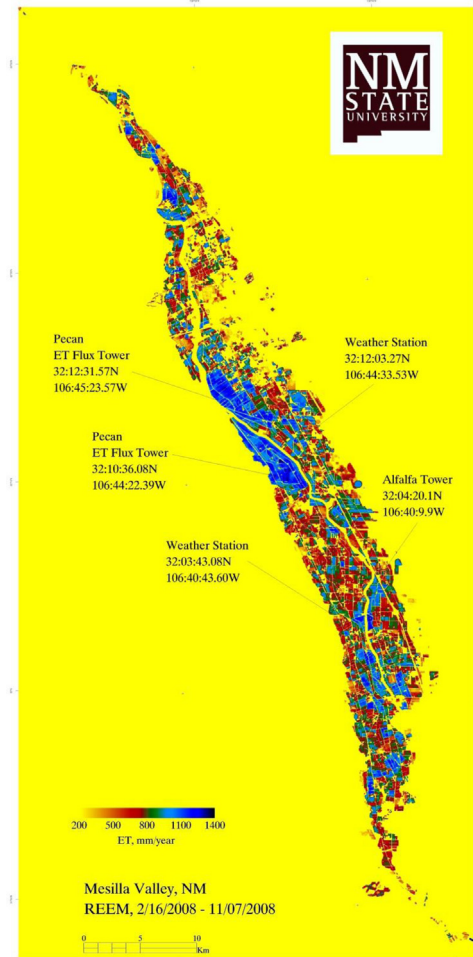


Fig. 1. ET distribution in New Mexico's Lower Rio Grande (LRG) for year 2008 and location of eddy covariance flux towers and weather stations.

to zero and estimating instantaneous  $R_{ni}$  and ground flux  $G_i$  from Eqs. (4) and (6). The  $H_i$  value for the dry field was then calculated as a residual of the energy balance as:

$$H_i = R_{ni} - G_i \quad (6)$$

Daily crop ET and crop coefficient ( $K_c$ ) were calculated within the LRG watershed using 11 satellite images from Landsat-5 and Landsat-7 during 2008. A crop classification survey conducted by the New Mexico Office of the State Engineer in 2008 made it possible to calculate crop ET for individual fields throughout the LRG basin.

The instantaneous ground flux ( $G_i$ ) was estimated using an equation developed by Samani et al. (2006) where the ratio of  $G_i$  to  $R_{ni}$  is calculated as a function of Normalized Difference Vegetation Index (NDVI):

$$\frac{G_i}{R_{ni}} = 0.26e^{(-1.97 \text{NDVI})} \quad (7)$$

Daily crop ET and  $K_c$  values were developed for each pixel for the days when satellite images were available. The daily  $K_c$  values combined with daily standardized reference  $ET_{sz}$  were used to interpolate  $K_c$  values and to calculate daily crop ET for each pixel. The ET values for each pixel were then integrated within each shape files representing a field, to calculate average ET of each field for each day of the growing season. The ET values for the growing season were summed to calculate seasonal ET values for each field.

**Table 1**  
Theoretical and remotely sensed seasonal crop ET values in New Mexico's Lower Rio Grande (LRG) for year 2008.

Crop	Number of fields	ET remote sensing, mm	Theoretical ET, mm
Alfalfa	751	386–1217	1451
Pecan	1375	275–1223	1262
Cotton	577	350–879	904

## 2.2. On-farm irrigation efficiency

On-farm irrigation efficiency was calculated using the equation:

$$\text{Eff} = \frac{\text{ET} - \text{Re}}{\text{FDR}} \quad (8)$$

where Eff is on-farm irrigation efficiency, ET (mm) is seasonal evapotranspiration calculated using remote sensing, Re is the effective precipitation during the growing season, and FDR is field delivery (e.g., the sum of applied groundwater plus applied surface water). The irrigation efficiency defined in Eq. (8) is consistent with the methods used by New Mexico adjudication courts to establish FDR. Effective precipitation was calculated on a monthly basis for each field using monthly ET and monthly precipitation values for each field based on an equation provided by USDA-SCS (1967):

$$\text{Re} = 25.4 \times \left( 0.70917 \left( \frac{\text{Rt}}{25.4} \right)^{0.82416} - 0.11556 \right) \times (10^{0.02426(\text{ET}_m/25.4)}) \quad (9)$$

where Re is the effective monthly precipitation in mm, Rt is the total monthly precipitation in mm and  $\text{ET}_m$  is the cumulative monthly evapotranspiration in mm. If rainfall (Rt) was less than 1.85 mm, the Re was set equal to zero. The net irrigation application was assumed to be 76 mm (3 in.). The assumption of 76 mm was based on review of LRG soil physical properties. The soil survey of the study area indicates that readily available water (RAW) within the three-foot root zone of the soils ranges from 2 to 4 in. with an average of 3 in. (76 mm) (USDA-SCS, 1980). The difference between the RAW of two versus 4 in. is 5% effective rainfall, which translates into less than a 0.5% difference in estimated irrigation efficiency.

To calculate the FDR, 2012 groundwater pumping records from the New Mexico Office of the State Engineer (OSE) were combined with surface water delivery record from the Elephant Butte Irrigation District (EBID). Only fields with dedicated irrigation wells and unique EBID records were included in the study. Fields receiving water from one or more wells which also serve other fields or fields combined with other parcels in irrigation district account records were not included in the study because it was not possible to determine how much water was applied to a specific parcel of land. Farm-level irrigation efficiency values were calculated for the main crops of alfalfa, cotton and pecan which account for about 80% of LRG irrigated acreage.

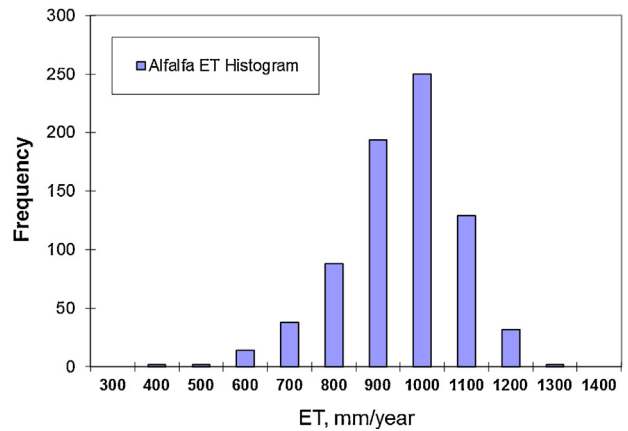
## 3. Results and discussion

The results of ET studies for alfalfa, cotton and pecans are shown in Figs. 2–4 and Table 1.

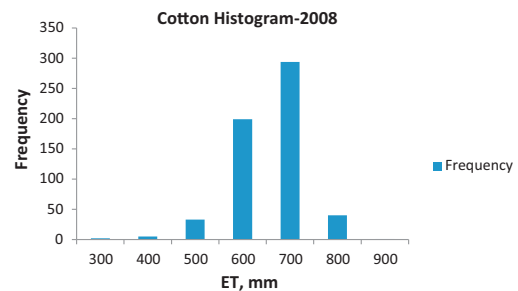
Theoretically, crop ET can be calculated using the crop coefficient ( $K_c$ ) multiplied by reference evapotranspiration ( $\text{ET}_r$ ) as:

$$\text{ET} = K_c \times \text{ET}_r \quad (10)$$

$\text{ET}_r$  can be calculated using various equations such as Hargreaves and Samani (1982, 1985) and Penman-Monteith (Allen, 1986), Allen et al. (1998) and ASCE-EWRI standardized reference evapotranspiration (2005). While theoretical calculation of ET for a given crop during a growing season is only one value, actual watershed-scale



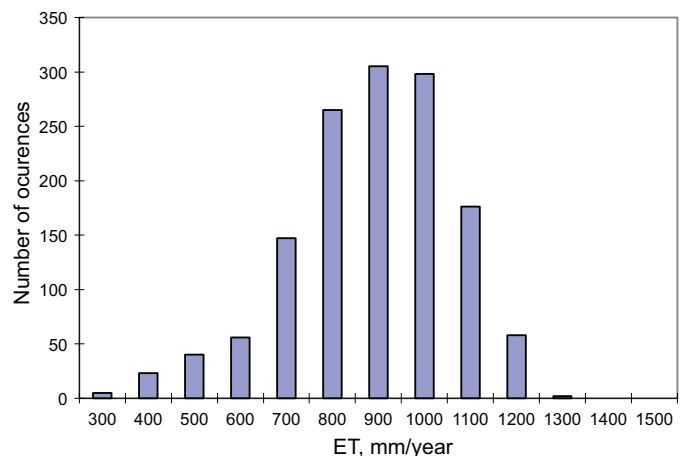
**Fig. 2.** Number of occurrences versus annual crop ET for 751 alfalfa fields in New Mexico's Lower Rio Grande (LRG) for year 2008.



**Fig. 3.** Number of occurrences versus annual crop ET for 577 cotton fields in New Mexico's Lower Rio Grande (LRG) for year 2008.

ET consists of histograms representing a range of values for fields in the watershed. The ET histograms often resemble random distributions (Samani et al., 2007a,b).

Table 1 compares the range of seasonal ET values with the theoretically calculated ET for the year 2008 in New Mexico's LRG. The results in Figs. 2–4 show that only a small fraction of the fields were within the range of theoretically optimum ET for well-watered, healthy, disease-and-insect-free, actively growing, and overall well-managed crops. For example, only 50 fields among the 1375 pecan fields had ET values close to the theoretically optimum ET. Among the 577 fields of cotton, only one field had an ET value close to the optimum value of 904 mm. Of the 751 alfalfa fields, all the ET values were below the theoretically optimum value of



**Fig. 4.** Number of occurrences versus annual crop ET for 1375 pecan fields in New Mexico's Lower Rio Grande (LRG) for year 2008.

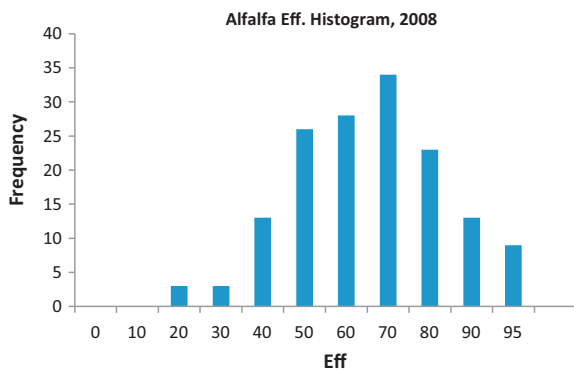


Fig. 5. Number of occurrences of seasonal on-farm efficiency for 152 alfalfa fields in New Mexico's Lower Rio Grande (LRG) for year 2008.

1451 mm. Figs. 5–7 show the histograms of irrigation efficiency for alfalfa, cotton and pecans in the LRG.

The histograms of irrigation efficiency are similar to histograms of ET where the values are scattered around a mean value similar to random probability distribution. The irrigation efficiency for each crop varies significantly ranging from low to high irrigation efficiency. Shearer and Vomocil (1981) stated that “behavioral patterns and value judgments of growers may have been the dominant cause for lack of sustained adoption of modern irrigation scheduling.” Table 2 shows the range and the average value of efficiency for the three crops.

Examination of individual fields in the LRG show that low irrigation efficiency is often associated with sandy soil, long runs, low flow rates, undersized turnouts and poor irrigation management (Skaggs and Samani, 2005a,b). However, the high efficiency

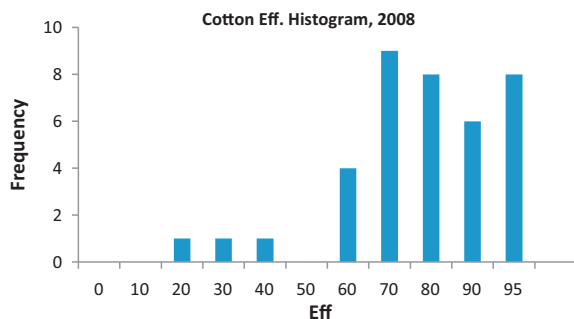


Fig. 6. Number of occurrences of seasonal on-farm efficiency for 38 cotton fields in New Mexico's Lower Rio Grande (LRG) for year 2008.

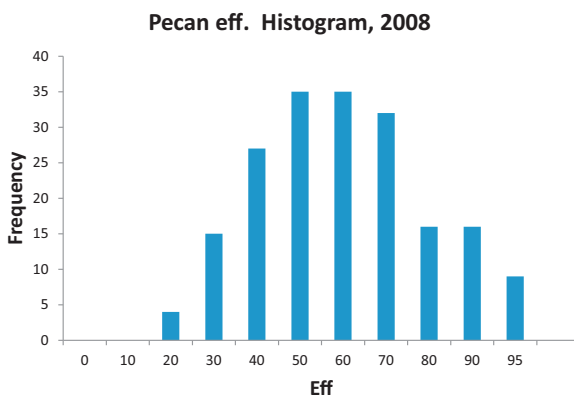


Fig. 7. Number of occurrences of seasonal on-farm efficiency for 189 pecan fields in New Mexico's Lower Rio Grande (LRG) for year 2008.

values do not necessarily reflect good water management and are often the result of deficit irrigation (Al-Jamal et al., 1997) and shallow groundwater contribution to ET. Two of the best-managed pecan orchards in the area were found to have irrigation efficiency values ranging from 57 to 63% in an earlier study (Sammis et al., 2004). The weighted average (by land area) on-farm irrigation efficiency for all three crops from this study was 64%. Wilson (1998) calculated average on-farm irrigation efficiency in the LRG using cropping pattern, estimated consumptive use and on-farm delivery records. Wilson's (1998) reported average on-farm irrigation efficiency was 60%. Al-Jamal et al. (1997) used the chloride technique on a small number of LRG farms and reported on-farm irrigation efficiency ranging from 70 to 97%.

The on-farm irrigation efficiency used in a recent water rights settlement between the Office of the State Engineer and the New Mexico Pecan Growers was 72% (Skaggs et al., 2011). The average on-farm efficiency of 64% found in this study corresponds to irrigation efficiency values previously estimated for deep rooted crops, although the LRG basin has approximately 3% of its irrigated land area planted to shallow rooted crops such as onions, lettuce, chile and cabbage.

The average on-farm irrigation efficiency for the entire LRG watershed also was calculated for 3 years using remote sensing, field delivery records and Eq. (8). The results are shown in Table 3.

The results of the basin-wide average efficiency analysis for the 3 years shown in Table 3 are within the range of the 64% obtained using remotely sensed ET estimates, EBID water delivery records for hundreds of individual fields, and groundwater diversions reported by the New Mexico Office of the State Engineer (2012). Table 4 compares the results of LRG on-farm irrigation efficiency in this study with the results reported by other investigators.

#### 4. District efficiency

Conveyance efficiency for the Elephant Butte Irrigation District was reported by Magallanez and Samani (2002) to be 54%. Using the on-farm efficiency of 64% and conveyance efficiency of 54%, the overall EBID district efficiency is calculated as:

$$\text{District efficiency} = (0.64) \times (0.54) = 0.35 \quad (11)$$

The calculated on-farm efficiency for the LRG shows that during 2008, 63% of the water was “lost” (Table 3). However, not all the 63% can be considered as truly lost water. The low district efficiency in LRG has historically maintained groundwater levels in the LRGs Mesilla Valley through recharge from on-farm irrigation and delivery seepage. Groundwater has declined during dry years and been replenished during wet years, resulting in relatively stable groundwater during the history of irrigation in the Mesilla Valley.

The analysis presented above is based on the classical definition of irrigation efficiency, which is a spatial concept; however, within the hydrological domain of New Mexico's LRG, what is traditionally defined as “lost” water can potentially be stored in the unconfined shallow aquifer and recovered through pumping at a later date. The stored water can be applied to a growing crop in the same year or in subsequent years. This characteristic is analog to a tailwater recovery system, although recovery of the seepage water can occur relatively quickly or over an extended period of time (e.g., one or

Table 2

Summary of average seasonal irrigation efficiency for alfalfa, cotton and pecans for New Mexico's Lower Rio Grande (LRG) for year 2008.

Crop	Irrigation Eff. % range average	No. fields
Alfalfa	11–95 (65.1)	152
Pecans	14.5–95 (59.7)	189
Cotton	11–95 (76.3)	38



**Table 3**

New Mexico's Lower Rio Grande average on-farm irrigation efficiency for three years, 2008–2011.

Year	EBID surface water allotment (mm)	Groundwater diversion (mm)	Total water applied (mm)	(ET-Re) REEM (mm)	Eff. %
2008	914	115.8	1029.8	643.1	63
2010	609.6	463.3	1072.9	707	66
2011	100.6	939.4	1040	676.7	65

**Table 4**

Comparison of seasonal on-farm irrigation efficiency in New Mexico's Lower Rio Grande (LRG) by various investigators.

Reference	Seasonal on-farm efficiency in LRG, %	Average, %
This paper	11–95	63
Al-Jamal et al. (1997)	70–97	N/A
Wilson (1998)	N/A	60

more years). The dynamic nature of irrigation efficiency is often lost in the classical approach to irrigation efficiency at local and temporal scales focusing on discrete time periods.

The year 2008 was a relatively wet year with above average available water. The surface water allotment from EBID was 3 acre-ft/acre (0.915 ha-m/ha). During 2008, farmers supplemented their allotted surface water supplies with an extra 0.38 ft (0.116 m) of pumped groundwater (New Mexico Office of the State Engineer, 2012); however, pumping did not result in declining groundwater because recharge exceeded the pumping rate. Therefore while the apparent on-farm irrigation efficiency was 63%, the net on-farm efficiency was actually equal to 70% accounting for the 0.116 m of “lost” water recovered through groundwater pumping within the same basin. Therefore in 2008, approximately 62% of the district's diverted water flowed to water users in other downstream irrigation districts. The lost water was due to groundwater overflow into drains and surface water spills. Alternatively, during 2011 (a dry year with only 0.33 ft (0.1 m) of surface water allotment), the majority of irrigation water applied to crops was pumped from the groundwater supply which had been recharged by water “lost” during previously wet years. In 2011, the calculated on-farm irrigation efficiency was 65%, but all the apparently on-farm lost water was stored in the groundwater since the drains were dry and there was no groundwater overflow in that year. Therefore, the 2011 net on-farm irrigation efficiency was practically 100% and the net district efficiency considering the negligible surface allotment of 0.1 m, was almost 100%.

## 5. Conclusions

The results of this study show that average on-farm irrigation efficiency in the LRG basin is between 63 and 66% with average of 64%. The overall district efficiency is 35%. While the average on-farm efficiency is within the range of what can be expected from surface irrigation techniques, there is significant spatial variability in irrigation efficiency between fields and farms. The low efficiency values can be attributed to design as well as management factors; and high efficiency does not necessarily imply a well-managed field. The reasons for the spatial variability of ET include the diversity of factors such as soils, crop cultural practices, economic factors, behavior patterns and management decisions by individual growers and the various resource constraints that producers face on daily basis (Skaggs and Samani, 2005a,b; Skaggs et al., 2011).

The LRG basin is currently going through water rights adjudication. Through negotiations with all stakeholders and a subsequent court order, the farm delivery requirement (FDR) has been determined to be 4.5 acre-ft per acre per year (1371.6 mm), with an assumed consumptive irrigation requirement (CIR) of 4.0 acre-ft per acre per year (1219.2 mm) for all crops. The negotiations also give irrigators the opportunity to claim an FDR of up to 5.5 acre-ft

per acre per year (1676.4 mm) if they can prove the historically higher water use.<sup>3</sup>

As water becomes more valuable and scarce, farmers will face economic incentives for implementing more efficient irrigation schemes. Understanding the value of irrigation efficiency across the watershed provides a powerful tool for economic analysis of alternative irrigation schemes. Government supported cost-sharing conservation programs such as the USDA-Natural Resources Conservation Service Environmental Quality Incentives Program use information on irrigation efficiency for ranking program applicants and prioritizing the use of public funds.<sup>4</sup> Understanding irrigation efficiency within the LRG also has significant implications in defining adjudicated water duties and long term administration of water resources. The current average on-farm irrigation efficiency of 64% and district efficiency of 35% show there is significant potential for improving both on-farm and conveyance efficiencies. The results indicate that farmers have the potential to push on-farm efficiency up to 90–95% under different management scenarios or in response to economic incentives. This means that the current annual LRG depletion of 2.1–2.3 acre-ft per acre (Table 3) can potentially increase to 4.5 acre-ft per acre. Such an increase in depletion, due to technology and management changes, would disrupt the current hydrologic balance of the LRG basin and potentially threaten sustainable groundwater supplies, as has already occurred in other basins in New Mexico (Richards, 2008; Skaggs et al., 2012). According to a joint report by the Texas Water Development Board and the New Mexico Water Resources Research Institute (1997), recharge to the Mesilla Bolson aquifer along the Rio Grande is primarily due to infiltration from irrigated agriculture. Therefore any improvement in irrigation efficiency can directly reduce the recharge to the aquifer and result in depleting the historically stable Mesilla Bolson aquifer.

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<sup>3</sup> This policy can be found at [http://www.nmpecangrowers.us/Water%20Issue/STREAM\\_ISSUE.101\\_SETTLEMENT\\_AGREEMENT.6.11.pdf](http://www.nmpecangrowers.us/Water%20Issue/STREAM_ISSUE.101_SETTLEMENT_AGREEMENT.6.11.pdf).

<sup>4</sup> USDA-Natural Resources Conservation Service Environmental Quality Incentives Program (EQIP) application ranking questions for New Mexico's Lower Rio Grande can be found at [http://www.nm.nrcs.usda.gov/programs/eqip/2012/Ranking\\_Criteria/South\\_Area-Irrigated\\_Crop-Non-Tribal.pdf](http://www.nm.nrcs.usda.gov/programs/eqip/2012/Ranking_Criteria/South_Area-Irrigated_Crop-Non-Tribal.pdf).

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