

Measuring On-Farm Irrigation Efficiency with Chloride Tracing under Deficit Irrigation

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Abstract: Water is a limited resource in agricultural production in arid climates. Under such conditions, high irrigation efficiency can be obtained either through implementation of efficient irrigation systems such as drip or sprinkler systems or through the age-old practice of deficit irrigation with gravity systems. The method used to increase irrigation efficiency is often dictated by economic and/or social factors. In either case, the effectiveness of water management at the farm level needs to be evaluated by measuring irrigation efficiency. The objective of this study was to evaluate the irrigation efficiencies for three crops in Southern New Mexico using the chloride technique. The chloride technique is a simple method in which the natural chloride in the irrigation water is used as a tracer to estimate the leaching fraction and the irrigation efficiency at the farm level. Soil samples were collected from various fields in 15 cm increments to a depth of 180 cm at the end of the irrigation season. The samples were analyzed for moisture and chloride content. In addition to the chloride technique, on-farm irrigation efficiencies were measured using applied water, yield, and water production functions. Water production functions and yields were used to estimate total evapotranspiration while flow measurements were used to calculate the amount of applied water. The results showed that high irrigation efficiency can be accomplished using deficit irrigation. Irrigation efficiency values ranged from 83 to 98%. Irrigation efficiencies using the chloride technique were compared with efficiencies estimated from direct flow measurements. The differences between the two methods ranged from 2 to 11.4%. The results showed that even though the chloride technique is subject to sampling errors and simplified theoretical assumptions, it can be used to estimate on-farm irrigation efficiency with considerable accuracy.

DOI: 10.1061/(ASCE)0733-9437(2005)131:6(555)

CE Database subject headings: Irrigation systems; Farms; Agriculture; Chlorides; Water management; New Mexico.

Introduction

Water is a limited resource in the arid climate of southern New Mexico. The limited water supply and increasing demands have created the need to identify sources of water loss and water use as well as the economic returns from water under various conditions. Potential sources of water loss include seepage and runoff from delivery systems as well as seepage and runoff losses during on-farm irrigation practices. Irrigation systems such as drip and

sprinkler irrigation are often used to increase on-farm irrigation efficiency. Even gravity systems can achieve high irrigation efficiency if they are designed, maintained, and managed correctly. However, gravity systems are often associated with low irrigation efficiency. A survey of irrigation systems at the national level showed that out of 25.7 million ha of irrigated land in the United States, 50% of irrigation systems used are gravity flow, 45% are sprinkler, and 5% are drip irrigation (*Irrigation Journal*, 2001). In southern New Mexico, more than 95% of the irrigation systems are gravity flow, commonly known as surface irrigation. The major crops in the area are pecan, alfalfa and cotton, which are planted in 75% of the irrigated land. The remaining 25% is planted with vegetable crops such as onion and chile. The generally mild slopes and moderate to slow water intake of soils favor basin and basin-furrow irrigation. Alfalfa and pecan commonly use basin irrigation while cotton and vegetable crops use basin-furrow irrigation. The farmers receive water on a demand basis with a fixed allocation water right, usually 1 ha m/ha. The limited water supply has created an economic necessity for deficit irrigation, especially by commercial farmers. However, information on the efficiency of on-farm irrigation application, the level of deficit irrigation, and the economic return from water is limited. The purpose of this study was to evaluate on-farm irrigation efficiencies for various crops in southern New Mexico using the chloride technique and to verify the technique using direct flow measurements.

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Note. Discussion open until May 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this technical note was submitted for review and possible publication on October 28, 2003; approved on October 29, 2004. This technical note is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 131, No. 6, December 1, 2005. ©ASCE, ISSN 0733-9437/2005/6-555-559/\$25.00.

Methodology

The concept of irrigation efficiency has been used to evaluate water management for many years. There are various definitions for irrigation efficiency (Willardson et al. 1994). Traditionally, irrigation efficiency is defined as the quantity of crop evapotranspiration supplied by irrigation divided by the quantity of applied water (Jensen 1981; Willardson et al. 1994).

The leaching fraction (LF) is the fraction of applied water which is lost below the root zone of the crop and therefore not available for crop use. If the leaching fraction is known, then the irrigation efficiency (IE) can be calculated as

$$IE = 1 - LF \quad (1)$$

Chloride is a nonreactive mobile element in the soil and water environments which can be effectively used as a natural tracer to evaluate the fate and transport of soluble nutrients in water (Prat et al. 1978; Stewart 1978; Al-Jamal et al. 1997; Vengosh and Pankratov 1998; Karr et al. 2001; Genereux et al. 2002). Chloride in irrigation water is either taken up by the plant or remains in the water in the soil. Using a simple mass balance in chloride transport, and assuming steady state conditions, Pratt et al. (1978) calculated the irrigation LF as

$$LF = \frac{V_p}{V_i} = \frac{Cl_i}{Cl_p} \quad (2)$$

where V_p =cumulative drainage flux (kg/ha); V_i =cumulative irrigation water applied (kg/ha); Cl_i =concentration of chloride in irrigation water (kg of Cl^- /kg of irrigation water); and Cl_p =concentration of chloride in drainage water (kg of Cl^- /kg of soil water). Eq. (2) assumes steady-state conditions and a single source of irrigation water with no chloride uptake by the crop. In southern New Mexico, crops are irrigated primarily using river water, but additional supplemental irrigation is provided through water wells that have considerably higher salt and chloride concentrations than the river water. Eq. (2) was modified to account for these multiple sources and sinks of the Cl^- as follows:

$$V_i + \sum_1^n V_n = V_p + ET \quad (3)$$

and

$$(V_i)(Cl_i) + \sum_1^n (V_n)(Cl_n) = (V_p)(Cl_p) + Cl_c \quad (4)$$

where V_i and Cl_i =amount and chloride concentration of the primary source of irrigation water; and V_n and Cl_n =irrigation amount and chloride concentrations from supplemental irrigation sources, respectively. Cl_c =chloride uptake by plant (kg/ha); and ET =seasonal crop evapotranspiration (kg/ha).

Combing Eqs. (2)–(4) results in the following equation for leaching fraction:

$$LF = \frac{Cl_i(ET) - Cl_c - \sum_1^n V_n(Cl_i - Cl_n)}{Cl_p(ET) - Cl_c - \sum_1^n V_n(Cl_i - Cl_n)} \quad (5)$$

If a single source of water is used for irrigation, then Eq. (5) can be simplified into

$$LF = \frac{Cl_i(ET) - Cl_c}{Cl_p(ET) - Cl_c} \quad (6)$$

Eqs. (2)–(6) assume steady-state conditions where the soil–water content remains constant over time. However, under real field conditions, steady-state conditions would be difficult to achieve, unless light, and frequent irrigation practices are used (Olson 1978). The assumption of chloride as a nonreactive element would be invalid if chloride precipitation occurs in the soil (Stewart 1978). Despite the limitations, the chloride method was selected for this study because it provides a simple and low cost method for estimating irrigation efficiency.

If the seasonal evapotranspiration (ET) can be estimated, then Eq. (6) can be used to calculate the LF and irrigation efficiency. The seasonal ET can be estimated using yield and crop water production functions. In the absence of ET values, irrigation efficiency can still be estimated from Eq. (6) by ignoring the plant chloride uptake (Cl_c). The plant chloride uptake constitutes only a small fraction of the total chloride flux and its effect on estimating irrigation efficiency is minimal (<3%, Alkhateeri 2001). When irrigation efficiency is calculated, the amount of water applied to the field can also be estimated by dividing the ET by the irrigation efficiency. This provides valuable information on irrigation deliveries at the field turnouts where water measuring devices are not commonly used. In cases where supplemental irrigation is implemented, Eq. (5) can be used to estimate LF and irrigation efficiency, but the amount and chloride concentration of supplemental water needs to be directly measured. It is often easier and more economical to measure the cumulative pump discharge with conventional flow meters rather than measuring the highly variable canal water discharge.

A total of 15 fields were included in the study, for the three major crops of alfalfa, cotton, and pecan. Ten fields were used to estimate irrigation efficiencies over a 3 year period. Five more fields were used for the verification of chloride methods. The field sizes ranged from 4 to 50 ha. All fields were in the Elephant Butte Irrigation District in southern New Mexico. All fields were irrigated using basin irrigation with no runoff. Fields were selected based on availability, access, and adequacy of information on yield and applied water. The data were collected over a period of 3 years and seasonal ET were calculated based on the reported yield, using the water production functions developed by various investigators in the area. Table 1 lists the crop water production functions for each crop.

The amount of chloride taken up by the crop was calculated by multiplying the various crop biomass (kg/ha) components by the chloride concentration in those components. Total biomass was calculated from yield and a harvest index except for alfalfa where yield was the total biomass. Harvest index was defined as the ratio of yield to total biomass (Sinclair 1998). Harvest index was measured by sampling a 1 m² area in the field. The total yield information were obtained from farmers after the harvest. To measure the chloride concentration in crop biomass, plant samples were dried at 68°C and were ground to pass a Number 20 mesh screen. Plant water extract were prepared by adding 25 mL of distilled water to 1 g of ground and sieved plant material, shaken for 15 min, and filtered through Whatman Number 42 filter paper (Bower and Wilcox 1965). Plant extracts were analyzed for chloride concentration using a digital HACH spectrophotometer at the New Mexico State University (NMSU) Soil and Water Testing Laboratory. Irrigation water samples

Table 1. Crop Water Production Functions for Various Crops in Southern New Mexico

Water production function	Crop	Reference
$Y=0.14+0.12*ET$	Alfalfa	Sammis (1981)
$Y=-12.1+0.5168*ET$	Green Chile	Wierenga (1983)
$Y=(134.87+14.25*ET)/1,000$	Cotton	Sammis (1981)
$Y=(-7,309+238.9*ET)/1,000$	Corn	Kallsen et al. (1981)
$Y=(-30.1+22.14*ET)/1,000$	Pecan	Miyamoto (1983)
$Y=-22,495.62+870.51*ET$	Onion	Al-Jamal (1995)
$Y=4,918.62+968.23*ET$	Lettuce	Cortez (1999)
$Y=-7,644.37+1,002.91*ET$	Cabbage	Cortez (1999)

Note: Y =yield in metric ton/ha and ET =seasonal evapotranspiration in centimeters.

Table 2. Results of Chloride Analysis for Alfalfa for 3 Years

Field	Soil type	Year	Yield (t/ha)	Relative yield	ET (estimated) (cm)	Leaching factor (%)	Irrigation efficiency (estimated) (%)	Applied water (estimated) (cm)
A-1	Loam	1996	20.78	0.7	172	2	98	175.5
A-1	Loam	1997	17.97	0.6	148	6	94	157.5
A-1	Loam	1998	18.0	0.6	149	4	96	155.2
A-2	Clay	1996	22.46	0.7	186	13	87	213.8
A-2	Clay	1997	20.21	0.6	167	11	89	187.6
A-2	Clay	1998	18.42	0.6	152	5	95	160.0

Table 3. Results of Chloride Analysis for Pecan

Field	Soil type	Year	Yield (t/ha)	Relative yield	Evapotranspiration (estimated) (cm)	Leaching fraction (%)	Irrigation efficiency (estimated) (%)	Applied water (estimated) (cm)
B-1	Sand	1996	2.02	0.7	92.5	6	94	98.4
B-1	Sand	1997	3.03	1.0	138	7	93	148.4
B-1	Sand	1998	1.8	0.6	82.4	7	93	88.6

Table 4. Results of Chloride Analysis for Cotton

Field	Soil type	Year	Yield (t/ha)	Relative yield	Evapotranspiration (estimated) (cm)	Leaching fraction (%)	Irrigation Efficiency (estimated) (%)	Applied water (estimated) (cm)
C-1	Sand	1996	1.235	0.6	77.2	4	96	80.42
C-1	Sand	1997	1.06	0.5	64.9	6	94	69.0
C-1	Sand	1998	1.404	0.7	89.0	6	94	94.7

Table 5. Comparison between Irrigation Efficiencies for Alfalfa, Pecan, and Cotton Using Two Methods for Estimating Irrigation Efficiencies

Field	Soil type	Year	Crop	Yield (t/ha)	Evapotranspiration estimated from yield (cm)	Irrigation efficiency chloride method (%)	Irrigation efficiency from measured water and yield (%)	Applied water (measured) (cm)	Difference in irrigation efficiency (%)
G-1	Loamy-sand	2000	Alfalfa	19.77	163.6	91	93	176	2
G-2	Sandy-loam	2000	Alfalfa	11.08	91	83	73.4	124	11.4
H-1	Loam	2001	Pecan	1.68	77	92	83	93	10
K-1	Loam	1988	Pecan	2.35	107.5	98	88	122	10
L-1	Loam	2000	Cotton	1.29	81	96	89	91	7

were collected at the beginning, middle, and end of the growing season to evaluate the average value of chloride concentration in the irrigation water. The crops were irrigated either from a single source of water (river water) or a combination of river and well water. In cases where well water was used, the chloride concentration in the well water was measured through periodic sampling. The effect of rainfall on the chloride concentration was not included in this study. The average annual rainfall in southern New Mexico is 200 mm. The rainfall is highly variable both spatially and temporally. No information is available on the effect of rainfall on crop ET or the fraction of rainfall interception by the plant. Due to the light (often less than 5 mm) and frequent nature of rainfall events, it is likely that most of the rainfall gets intercepted by the crop and has minimal effect on the soil chloride balance. Alkhateeri (2001) compared the estimated values of irrigation efficiency with and without rainfall. Assuming no rainfall interception, Alkhateeri (2001) showed that if the rainfall is ignored, the irrigation efficiency can be underestimated by as much as 1.2%.

Field sizes varied from 5 to 40 ha with soil texture ranging from clay to sand (Tables 2–4). At the end of growing season, the fields were divided into four equal sections. Two locations in the middle of each section were sampled for soil cores. Samples were taken in 15 cm increments from 15 to 180 cm of depth using a 7.62 cm diameter bucket auger. Gravimetric soil moisture contents were measured for each sample immediately after sampling in order to minimize error due to water loss. Chloride concentration in soil samples were measured by preparing a saturated extract with distilled water. Soil–water extracts were prepared by adding 25 mL of distilled water to 5 g of dry soil, shaking for 2 h, and filtering through Whatman No. 42 filter paper (Bower and Wilcox 1965). The extracts were then analyzed for chloride concentration using a digital HACH spectrophotometer. Once the ET was estimated from the crop yield, Eqs. (5) and (1) were used to calculate the LF and irrigation efficiency. The amount of irrigation water applied to the field was estimated by dividing the ET by the irrigation efficiency.

Results and Analysis

Tables 2–4 summarize the results of the chloride analysis and the estimated irrigation efficiencies for three crops during 1996–1998. All sites were irrigated from a single source of water and none of the site had flow measuring devices. The irrigation efficiencies in Tables 2–4 were measured using the chloride technique described in this paper. The high irrigation efficiencies of all three crops are attributed to the practice of deficit irrigation. Deficit irrigation is an irrigation practice where the applied water is less than the amount of water required for optimum crop growth.

The purpose of deficit irrigation is to maximize the yield from a unit of water rather than maximizing the yield from a unit of land. Deficit irrigation is a tradition in dry climates of the world where the limited water supplies are stretched over large crop areas in order to maximize total economic return (Hargreaves and Samani 1984).

The exception was the field B-1, where a high irrigation efficiency was obtained by using high flow turnout in a basin irrigation system combined with laser leveled field and irrigation scheduling.

Field Verification

In order to verify the accuracy of the chloride analysis, five independent fields in the Elephant Butte irrigation district were identified where flow measurement devices had been installed and the amount of applied irrigation water was recorded. In Table 5, alfalfa fields were irrigated from two sources (river and well), but pecan and cotton were irrigated from a single source (river water). The chloride method and yield data were used to estimate the total ET and irrigation efficiency. Irrigation efficiency was also calculated by dividing the estimated ET by the amount of measured applied water. The comparison is shown in Table 5.

This comparison shows that the chloride technique can provide reasonably accurate estimates of irrigation efficiencies at the field level. The chloride method combined with yield or ET information can also be used to estimate the total applied water when flow measuring devices are not available. Table 5 shows the chloride technique generally tends to overestimate the irrigation efficiency. The overestimation can be attributed to various factors including error in sampling and analysis, error in flow measurement, and off season evaporation or evapotranspiration and the difference between initial and final soil moisture.

Conclusions

Irrigation efficiencies were measured using the chloride tracer technique and direct field measurements of yield. Three crops and ten sites were used in the evaluation. The results showed that, contrary to conventional belief, high on-farm irrigation efficiencies can be obtained using surface irrigation. Irrigation efficiencies ranged from 83 to 98%. The high irrigation efficiencies in the area were mainly due to deficit irrigation, with the exception of one field, where a high irrigation efficiency was obtained due to use of high flow turnout, laser leveled field, and irrigation scheduling. The chloride technique is subject to potential error due to potential sampling and analysis errors, and simplified assumptions such as the assumption of steady-state flux. However, the comparison between efficiency values measured by the chloride method and the direct field measurement of applied water showed that on-farm irrigation efficiency can be measured using the chloride technique with good accuracy. The differences in irrigation efficiencies measured with the chloride technique and with direct flow and yield measurement ranged from 2 to 11.4%.

Notation

The following symbols are used in this technical note:

- Cl_c = chloride uptake by plant (kg/ha);
- Cl_i = chloride concentration in irrigation water (kg/kg);
- Cl_n = chloride concentration in water source n (kg/kg);
- Cl_p = chloride concentration in drainage water (kg/kg);
- ET = evapotranspiration (kg/ha);
- IE = irrigation efficiency;
- LF = leaching fraction;
- V_i = irrigation water from source i (kg/ha);
- V_n = irrigation water from source n (kg/ha); and
- V_p = drainage flux (kg/ha).

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