CONSUMPTIVE USE AND RETURN FLOWS IN URBAN WATER USE

by

Ramchand Oad and Michael DiSpigno, with contributions from David L. Nettles, State Engineer's Office, and Philip C. Saletta and Kevin D. Lusk, Colorado Springs Utilities Water Resources Department

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Ramchand Oad and Michael DiSpigno
Department of Chemical and Bioresource Engineering
Colorado State University

with contributions from

David L. Nettles
State Engineer's Office, Colorado Division of Water Resources

and

Philip C. Saletta and Kevin D. Lusk
Colorado Springs Utilities Water Resources Department

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Colorado Water Resources Research Institute
Colorado State University
Fort Collins, Colorado, 80523

Robert C. Ward, Director

ABSTRACT

This is a report of our research on issues related to return flow from irrigation of urban landscapes. Municipalities in Colorado with rights to transmountain water and other "use to extinction" water rights have examined lawn irrigation as a possible source to augment their supplies. They claim that a significant percentage of water applied to lawns is not used by the turf grass, and eventually returns to the streams and ground water systems. In accordance with their water rights, this deep percolation water can be reused by the municipalities. Return flow credits, therefore, involve significant amounts of additional water supply and financial benefits to municipalities.

To quantify irrigation-deep percolation relationship, municipalities have used small lysimeters whose accuracy in estimating turf grass consumptive use and deep percolation was not well established. To provide an independent analysis, research was conducted at the Colorado State University, CSU (1992-96). This paper presents the research findings on the accuracy of methodologies used by various cities to estimate deep percolation as a function of applied water. It also analyzes how these methodologies were evaluated by the Water Courts in their decisions concerning credits for return flow.

The CSU research results indicate that the small lysimeters used by various cities are of acceptable accuracy compared to a large lysimeter and standard evapotranspiration equations for estimating consumptive use. Also, there is no significant difference between the two types of small lysimeters used by municipalities -- drainage and weighing type small lysimeters -- to estimate deep percolation. For estimating deep percolation, results of this research support the findings of the previous studies conducted for the City of Colorado Spring (Gronning Line) and for the Cottonwood Water and Sanitation District in Denver (Cottonwood Curve).

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INTRODUCTION

Specific Water Problem

The western United States is experiencing rapid population growth which has placed increased demands on the limited natural resources of the region, most notably, water. It has become crucial for both agricultural and urban water users to protect their water rights and resources by careful accounting and planning processes. Many Colorado Front Range cities obtain a significant portion of their water supplies from transmountian sources, and as provided by Colorado water law, transmountain water can be "used to extinction." Colorado Springs, for example, acquires about 75% of its water supply from transmountain sources (Saletta and Kaufman, 1994). Municipalities with large transmountain water sources and other "use to extinction" water rights have examined landscape irrigation as a possible area to augment their water supplies. They believed that a percentage of the lawn irrigation water was not used by the turf grass, deep percolated through the turf grass root zone, and eventually became return flow to the stream and ground water systems. In accordance with their water rights, this deep percolation water can be reused by the municipalities (Wheeler, 1987; Gronning, 1989).

To quantify return flows several cities have used small lysimeters to estimate turf grass consumptive use and return flows. The accuracy of small lysimeters is not well known and the practice has been questioned by some who believe that small lysimeters predict inaccurate consumptive use and return flows. In response to these concerns, this research was sponsored by the Office of the State Engineer of Colorado, the City of Colorado Springs, and the Colorado Water Resources Research Institute.

Research Objectives

The overall goal of the research project was to evaluate methodologies used by various municipalities in Colorado for estimating deep percolation from urban lawn water use. The methodologies have used small lysimeters whose accuracy in estimating consumptive use and deep percolation was not well established. The other major objective was to check the validity of irrigation-return flow relationships developed by municipalities for claiming return flow credits. In this context, the specific research concerns were as follows.

- Accuracy of small lysimeters in estimating turf grass consumptive use,
- Amount of deep percolation as influenced by the amount of water applied,
- Amount of deep percolation as influenced by other factors such as the frequency of water applications and the soil type.

The research findings reported in this paper are based on the analysis of four-years data (1992-1995). The CSU results of deep percolation using small lysimeters are compared to two previous studies conducted for the Cottonwood Water and Sanitation District in Denver (Wheeler, 1987) and for the City of Colorado Springs (Gronning, 1989). Accuracy of small lysimeters in estimating consumptive use is evaluated by comparing evapotranspiration results obtained from the small lysimeters to those obtained from a standard large lysimeter and from the 1963 Penman Equation (Jensen et al., 1990).

DETERMINATIONS OF RETURN FLOW BY MUNICIPALITIES

In order to obtain return flow credit, municipalities must first quantify the components of the irrigation-return flow system. First, they must determine the amount or percentage of the application water which is not consumptively used by the turf grass and passes through the turf grass root zone (deep percolation water). Then, they must determine the amount or percentage of the deep percolation water that will eventually return to the stream and groundwater systems (return flow). The return flow is less than the deep percolation since trees, shrubs, and other landscape vegetation can consume deep percolation water, as well as additional consumption taking place during transit to the stream or groundwater system.

The Cottonwood District Study -- the Cottonwood Curve

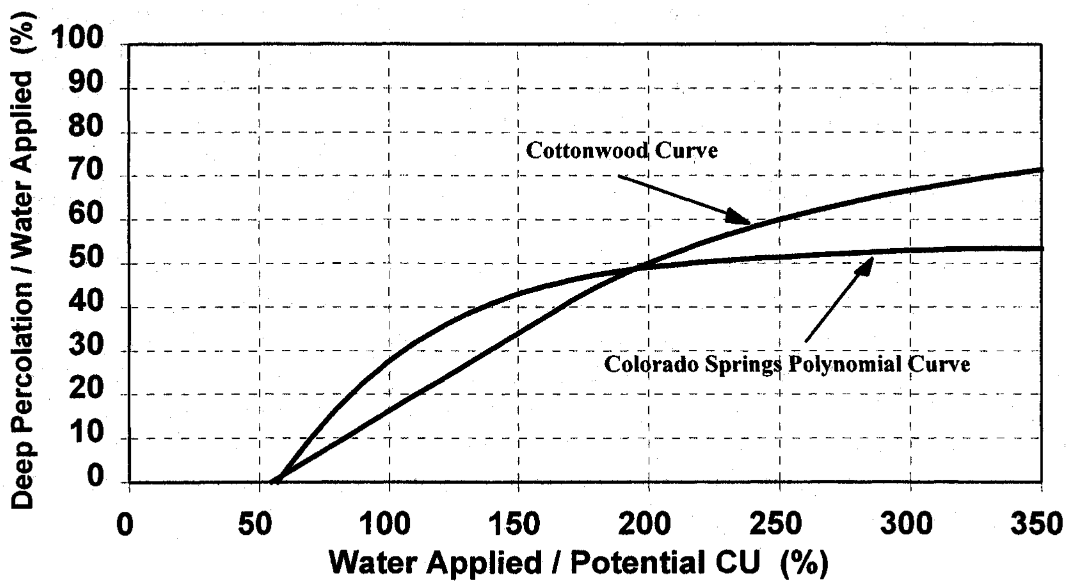
In 1983, the Cottonwood Water and Sanitation District retained consulting engineers W.W. Wheeler and Associates, and began a lysimeter study to quantify the amount of deep percolation from lawn irrigation. This was done as part of its augmentation plan filed in the Colorado Water Court (Case No. 81CW142). By 1984, forty, 30.5 cm diameter, weighing type lysimeters were installed in Cherry Creek and Denver's southeast metropolitan area. The "Cottonwood Curve" was developed from these data which demonstrates a relationship between water application, deep percolation, and potential consumptive use of turf grass using small lysimeters (Fig. 1).

Wheeler first developed a curve that it felt best represented the relationship between deep percolation (DP), water applied (WA), and potential consumptive use (CU) using all the data points and giving special consideration to the controlled lysimeters and the shape of the curve expected by physical reality (Wheeler, 1987). This "best fit" curve was linearized for WA/CU ratio less than 160, and slightly lowered (from 22% to 16% at 100% WA/CU) to form the Cottonwood Curve (Wheeler, 1987; Walter, 1996). Continued lysimeter studies by Wheeler in 1984-1986 reinforced the opinion that the Cottonwood Curve underestimated the amount of deep percolation from lawn irrigation (Wheeler, 1987). The Water Court accepted the results of the Cottonwood Curve, and other municipalities began using it when requesting return flow credits (Castle Rock, Case Number 84CW656; Centennial Water and Sanitation District, 85CW415; Westminster, 86CW397; and, Greeley, 87CW329) (Walter *et al.*, 1991).

Observing these Water Court proceedings, Colorado's Office of the State Engineer began accepting municipalities' requests for return flow credits of 15% of the water application. This number was arrived at by using the Cottonwood Curve and assuming:

- that water was applied to lawns at a rate equal to the rate of potential consumptive use (100% on the x-axis), and
- a reduction for consumptive use by trees and shrubs (tree canopy consumption). If municipalities requested a return flow credit greater than 15%, they were required to provide the engineering reports to document the validity of this request (Wolfe, 1996).

Due to the expense involved in generating these engineering reports and the legal fees involved in going to Water Court, many cities which filed for a water credit accepted, and continue to accept, the 15% water credit. The money they would have spent hiring engineering consultants and in litigation was used to acquire additional water rights.



Cottonwood Curve:

55 <WA/CU <160 DP/WA=0.357*WA/CU-19.6
WA/CU >160 DP/WA=100*(WA/CU-100)/(App/CU)

Colorado Springs Polynomial Curve:

DP/WA= -0.6993+1.6633(WA/CU)-0.8847*(WA/CU)^2+0.2147(WA/CU)^3-0.0197(WA/CU)^4

Fig.1. Deep Percolation as a Function of Applied Water -- Cottonwood and Gronning Curves

The City of Colorado Springs Study -- the Gronning Line

The city of Colorado Springs (approximate 1994 population: 309,000, average annual water use: 69,200 acre-ft; Saletta and Kaufman, 1994) believed that its return flows were substantially greater than 15% of the water application. In 1985, Colorado Springs retained consulting engineers, Gronning Engineering Company, and began its own lysimeter project. By 1986, Colorado Springs had installed eighty-six, 40 cm diameter, drainage type lysimeters throughout the city. Today the city still operates and maintains more than 90 lysimeters. Unlike the hand-packed soil profile lysimeters used in the Cottonwood study, the Colorado Springs lysimeters used an undisturbed soil core profile obtained from in situ lysimeter placement. The lysimeter results were presented in a different format than the Cottonwood Curve, and a straight line relationship, the "Gronning Line," was developed demonstrating the relationship between effective irrigation application and gross irrigation return flows.

From its 1987 and 1988 research, Colorado Springs determined that the average recharge in its study area was approximately 8,000 acre-ft per year, and the average gross irrigation return was approximately 37% of the total effective application (Gronning, 1989; Saletta and Kaufman, 1994). In 1989, Colorado Springs filed a claim with the Water Court (89CW36) claiming the right to reuse lawn irrigation return flows for all water derived from a reusable source. As part of these proceedings, Colorado Springs was required to present its lysimeter results in a Cottonwood-type format using the same definitions of the x- and y-axes. It developed the "Colorado Springs Polynomial Curve" (Fig. 1) which they believed more accurately described the unique Colorado Springs' conditions (such as soil and turf grass type, and irrigation practices of the town's people) which are different from those represented in the Cottonwood study. The polynomial curve was accepted by the Court, and Colorado Springs is able to use this curve when determining return flows (Saletta and Kaufman, 1994; Kaufman, 1994). Colorado Springs was "able to acquire about 3.5 cubic feet per second of reusable water for municipal purposes. Future reusable irrigation return flows may ultimately provide as much as 12,000 acre-feet of additional water per year" (Saletta and Kaufman, 1994).

Controversy Concerning the Cottonwood Curve and the Gronning Line

Although both the Cottonwood Curve and the Gronning Line are formatted based on practical applications, there is some controversy associated with their use. In the Cottonwood Curve, water application appears in both the x- and y-axes. This results in the following quadratic relationship between water application (WA), consumptive use (CU) and deep percolation (DP) in the 0% to 160% WA/CU range:

$$DP = (0.357\ (WA)^2/\ CU) - (19.6\ WA) \tag{1}$$

Based on the large variability in the lysimeter data, many people involved in deep percolation lysimeter research consider a quadratic relationship between deep percolation and water application to be more complex than required. It is suggested that a linear representation would be more appropriate.

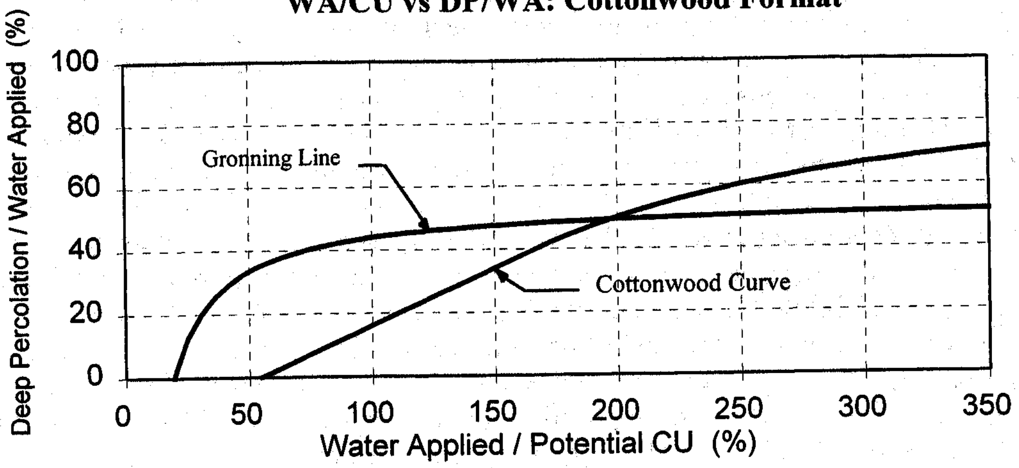
The Gronning Line, from which the Colorado Springs Polynomial is based, attempts to remove this quadratic relationship and reports the response between water application and deep percolation directly. However, the Gronning engineers modified both the water application and deep percolation parameters. They defined water application, not as the total water application to the lysimeter, but as the irrigation water applied (I) to each lysimeter (total water application minus precipitation). Deep percolation is calculated as the total drainage from the lysimeter minus the corresponding percentage due to precipitation. That is, if 30% of the total water application was precipitation, 30% of the drainage would be deducted from the drainage total (Kaufman, 1996). Using this format, the Gronning Line equation for net drainage (ND) is (Gronning, 1989):

$$ND = (0.546 * I) - 0.019 \tag{2}$$

The accuracy of the Gronning format is questionable since the removal of the precipitation component leads to a distortion of the results by significantly reducing the x-intercept, the application rate at which deep percolation first begins to occur. Deep percolation response is based on the total water application since turf grass can not differentiate between irrigation water and precipitation. The Gronning format ignores the precipitation component thereby modifying the deep percolation response. Along with the inconsistent format between the two studies, the Cottonwood Curve and the Gronning Line, have inconsistent results. Figure 2 shows the Cottonwood Curve and the Gronning Line in both formats. Note that due to the quadratic relationship of water application and deep percolation in the Cottonwood Curve, one function is linear and the other parabolic in each figure.

The different results between the two studies are due to several factors, the most significant being that the Gronning Line is based on precipitation being removed from the total water application. Another difference is that the two studies used soils specific to their sites, either dug from the lysimeter hole (Cottonwood) or using an undisturbed core (Gronning).
Both investigated the deep percolation response for their specific area. Other two factors affecting each study's outcome are the water application amount and frequency. Neither the Cottonwood nor the Colorado Springs studies were based on a regular irrigation amount and frequency. Both of these factors were controlled by the individual homeowners who watered their lawns when they felt it was necessary. This decision was based on homeowners' qualitative choice of how green they wanted their lawns to appear, balanced with the expense and labor associated with the lawn irrigations. Both studies are as much a "measure of human behavior" (Kaufman, 1996) of people in their areas as they are about turf grass deep percolation.

WA/CU vs DP/WA: Cottonwood Format

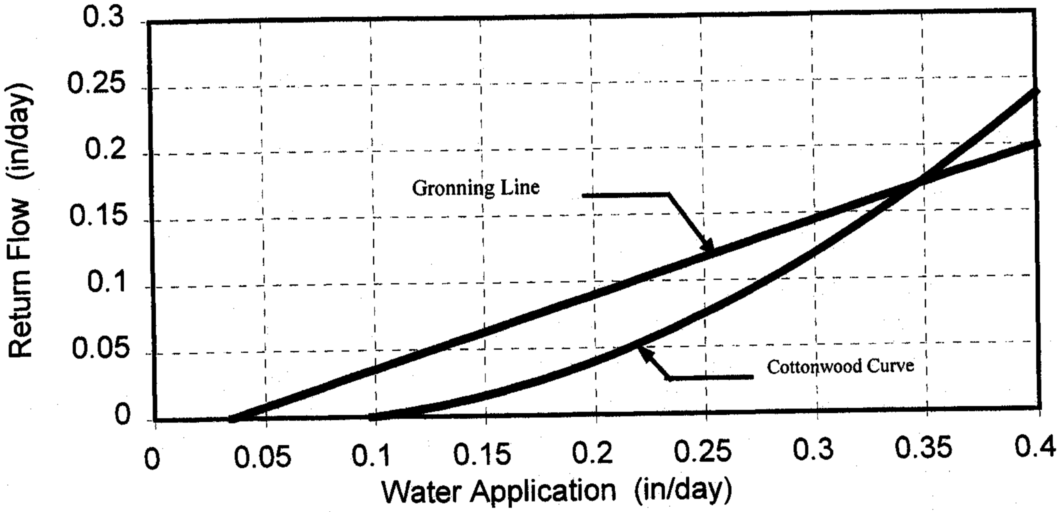


Assume:
CU = 700 mm/season, 153 days per season (May 1 - September 30)
Cottonwood Curve:

55<WA/CU<160	DP/WA = 0.357 * WA/CU - 19.6
WA/CU>160	DP/WA = 100 * (WA/CU-100) / (WA/CU)

Gronning Line:
WA' = IWA * 25.4 mm/in * 153 days/season
DP' = ((0.546 * IWA) - 0.019) * 25.4 mm/in * 153 days/season

Water Application vs Deep Percolation: Gronning Line Format



Gronning Line :
Net DP = (0.546 * IWA) - 0.019

Cottonwood Curve:
DP = 0.357 (WA^2)/CU - (0.196 *WA)

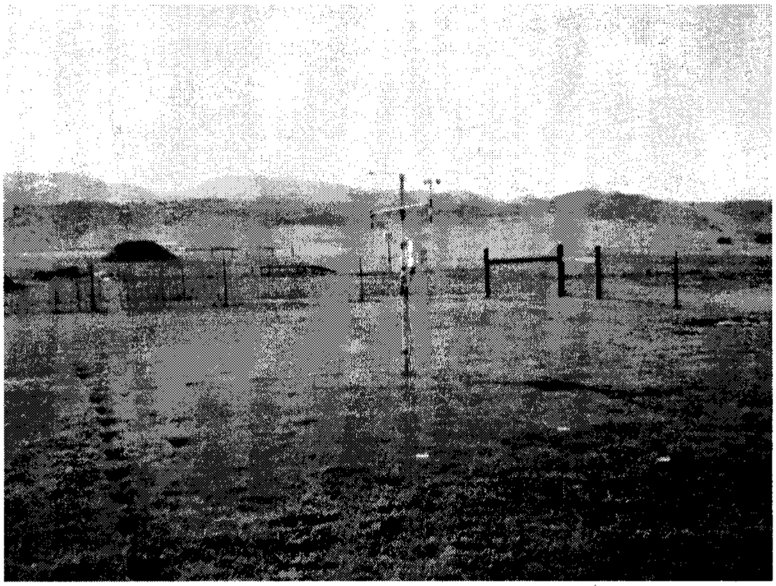
Assume:
CU = 700 mm/season
Season Lengh = 153 days
(May 1 - September 30)

Fig.2. Water Application -- Deep Percolation Relationship in Cottonwood and Gronning Formats

RESEARCH METHODS

Apparatus and Procedures

The study was conducted at the Agricultural Engineering Research Center located in Fort Collins, Colorado. This facility has an automated weather station, located on a turf grass plot with dimensions of 25m X 25m, which collects data needed to estimate potential ET using the Penman equation. A large lysimeter is also located on the plot and this lysimeter is used as the reference to which 24 small lysimeters are compared.


Weather station on turf grass plot

The study utilized two types of small lysimeters: a weighing type used for the Cottonwood Water and Sanitation District in Denver (Wheeler, 1987), and a drainage type used by the City of Colorado Springs (Gronning, 1989).

The control in this research is the large lysimeter which is a hydraulic weighing type with tank dimensions 1 m X 1 m X 1.3 m deep (Fig. 3). The annular to surface area ratio of the lysimeter is 0.08. The tank rests on two bearing plates which in turn rest on two flexible, hydraulically connected, fluid filled "pillows". A hydraulic line connects the pillows to a mercury manometer located in a control box.

The change in soil moisture in the lysimeter is translated to a hydraulic signal which is read on the manometer. A 0.3 m graduated gravel filter was placed in the bottom of the lysimeter tank to facilitate collection of drainage water. The drainage is collected by a vacuum line to the control box where a vacuum pump controlled by a timer removes the drainage water and collects it in a jar. On top of the filter, soil was packed into the lysimeter to a bulk density of 1.3 g/cm^3. Kentucky Bluegrass sod was installed on the surface of the tank.

The small weighing lysimeters were constructed from a 61-cm long section of 30.5 cm diameter PVC pipe with a small valve threaded into the bottom plate to collect drainage water (Fig. 4.a). These lysimeters are designed to be lifted out of the soil for weighing and drainage, and cable loops at the top act as points of attachment for a weighing and lifting apparatus. The annular to surface area ratio for this lysimeter is 0.07. The small drainage lysimeters consist of a 40 cm diameter steel pipe 61 cm in length with a fiberglass bottom cap (Fig. 4.b). A stand pipe is attached to the bottom of the cap and is run to the soil surface on the outside of the pipe section. The drainage

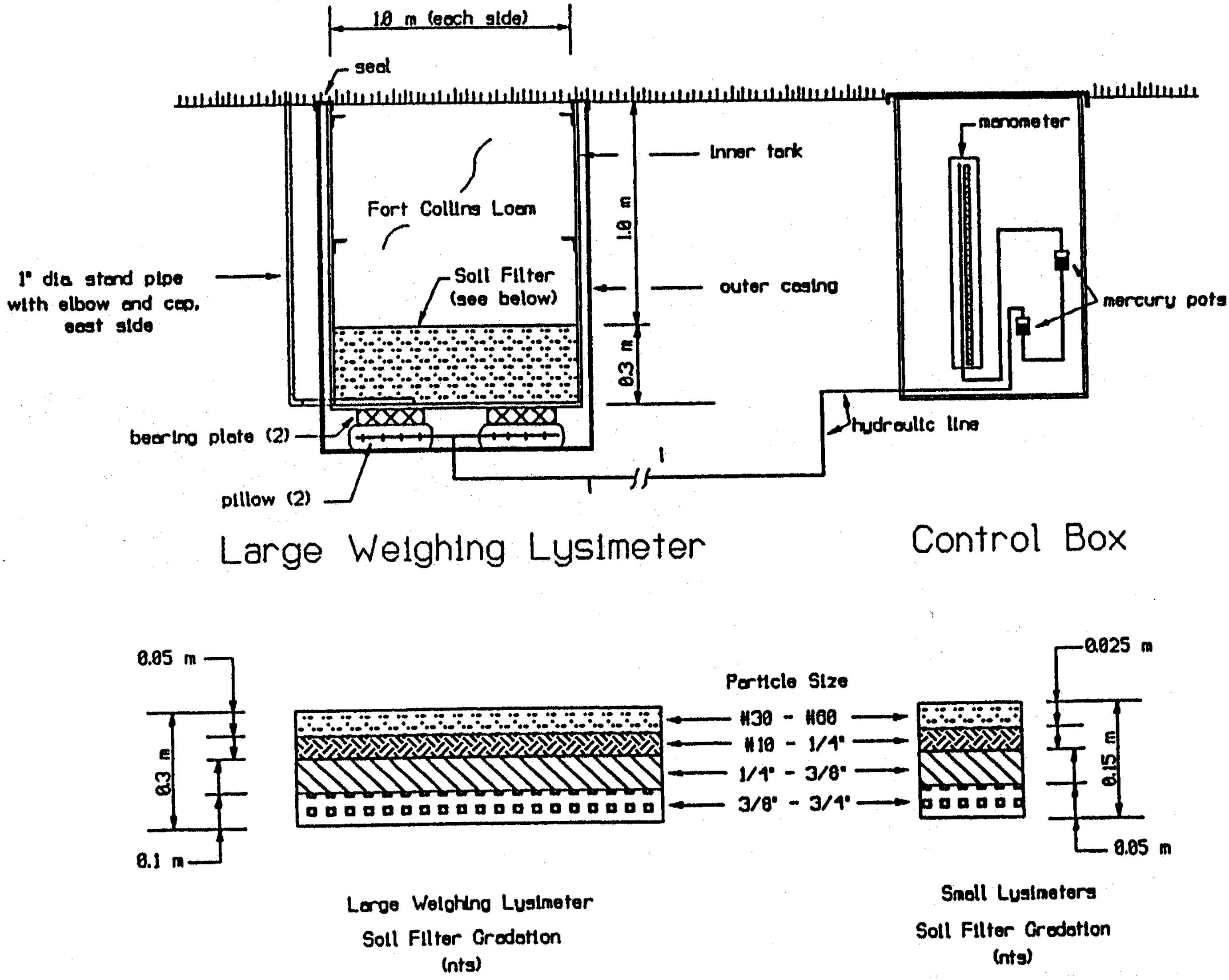


Fig. 3. Large Weighing Lysimeter

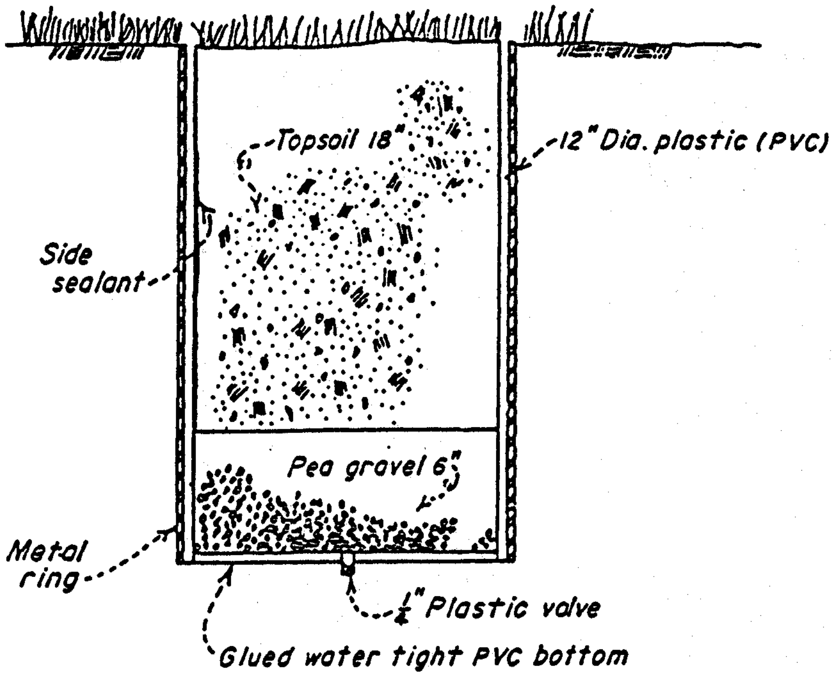


Fig. 4.a. Small Weighing-Type Lysimeter

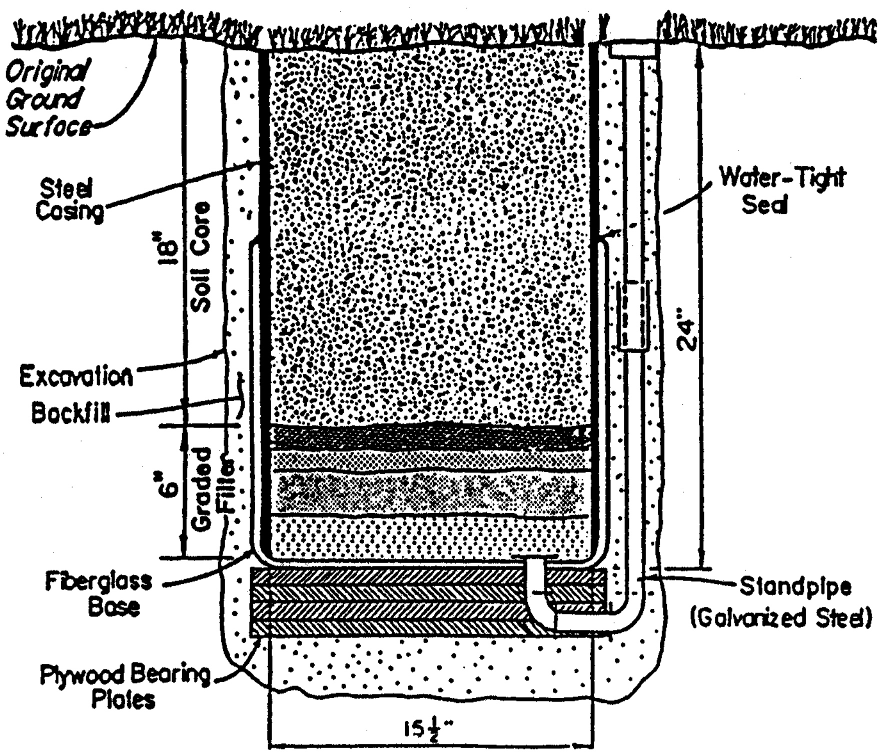


Fig. 4.b. Small Drainage-Type Lysimeter

Hydraulic, weighing-type lysimeter used as the control

lysimeter is permanently installed flush with the ground surface and sod is allowed to grow over the lip. The annular to surface area ratio is 0.06 for this lysimeter.

A 0.15-m filter pack similar in design to that in the large lysimeter was placed in the bottom of the small lysimeters and the soil was packed above this to a bulk density of 1.3 g/cm^3.

The study included four soil types chosen for their infiltration and water holding characteristics: a sandy loam, a loam, and a clay loam acquired from sites in the City of Colorado Springs, and a loam soil obtained from Fort Collins. Three replications of the sand, loam, and clay were placed in nine small weighing lysimeters and this was repeated for nine small drainage lysimeters. Fort Collins loam was placed in the large lysimeter and in three small weighing and three drainage lysimeters. As such, there were a total of twelve small weighing lysimeters and twelve small drainage lysimeters.

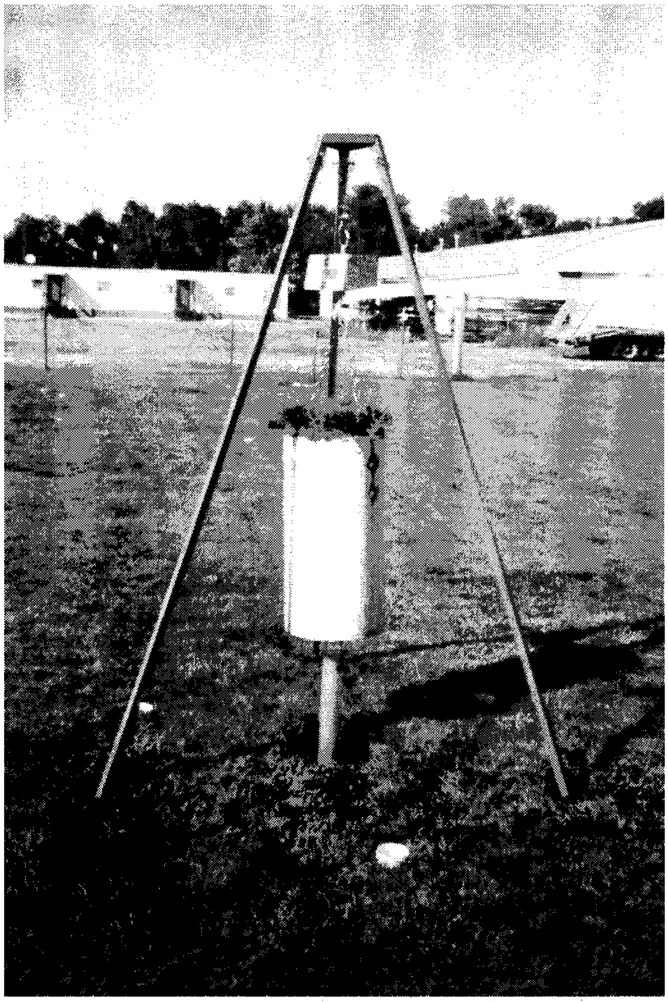
Data Collection and Analysis

The amount of water application, deep percolation and the change in soil moisture content were measured for four summer seasons (1992-95). Data for the large lysimeter were collected daily except on the weekends. The change in soil moisture (CSM) was found by subtracting the day's lysimeter weight from the previous day's lysimeter weight measurement. Deep percolation water (DP) was pumped out and measured, and the amount of water applied during each irrigation (I) was measured by using catch cans. Precipitation (P) was measured in a tipping bucket gauge and was assumed to be uniform over the entire study site. From these data, daily evapotranspiration (ET) was calculated from a volume balance equation,

$$ET = I + P - DP - CSM \qquad (3)$$

Data for the small lysimeters were collected twice a week. For the drainage lysimeters, deep percolation water was pumped out from the standpipe and the volume was measured. The drainage volume was converted to an equivalent depth, and evapotranspiration was found for the period since the last measurement using the volume balance equation (Eq. 3).

For the weighing lysimeters, additional data collected were the lysimeter weight and the amount of deep percolation and these were also taken the day after irrigation. The lysimeters were removed from the turf, weighed, drained, weighed again, and replaced. The change in soil moisture was calculated by subtracting the weight after draining from the similar weight measurement taken on the previous date of measurement. Evapotranspiration was derived from the volume balance equation.



Weighing-type lysimeter

RESULTS: EVALUATION OF MUNICIPALITIES' DETERMINATIONS

Evaluation of the Cottonwood Curve

Figure 5 shows the results of the four years data for all small lysimeters, and the Cottonwood Curve. A simple linear regression was performed on the data and the regression line and the 95% confidence interval are shown. The equation of the CSU regression line is:

$$DP/WA = (0.374\ WA/CU) - 20.44 \qquad (4)$$

The R^2 value for the regression is 0.41. As mentioned, the Cottonwood Curve is not the linear regression line for the Cottonwood lysimeter data but what the Wheeler engineers considered a conservative representation of the lysimeters' response. The Cottonwood curve is expressed by following equations.

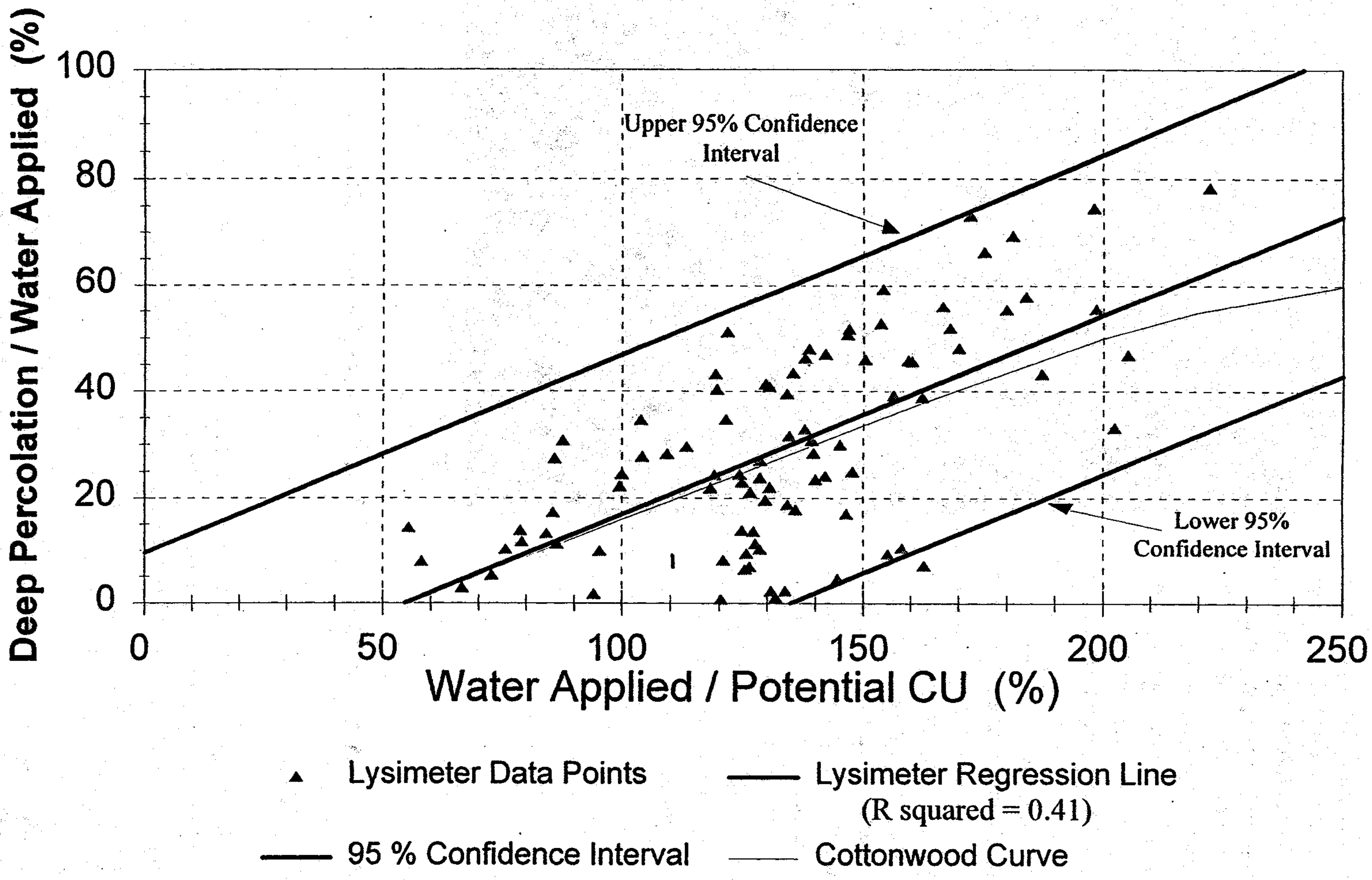


Fig. 5. Cottonwood Curve Compared to CSU Data

For $55 < WA/CU < 160$, $DP/WA = (0.357 * WA/CU) - 19.6$ (5)
For $WA/CU > 160$, $DP/WA = 100 (WA/CU - 100) / (WA/CU)$ (6)

As shown in Fig. 5, the CSU regression line and the linear part of the Cottonwood curve are very close to each other with very similar slopes and identical x-intercept points. The x-intercept point is significant since it indicates the amount of water applied, as percentage of consumptive use, below which no drainage will occur. The x-intercept point for both the CSU research data and the Cottonwood Curve is 55 percent.

Evaluation of the Gronning Line

Figure 6 presents four years' lysimeter data using a format based on total water application (WA) (irrigation plus precipitation) and total drainage. The CSU research results are compared with the Gronning Line (Gronning, 1989). The equation of the CSU regression line is,

$$DP = (0.793 * WA) - 0.113 \quad (7)$$

The R^2 value for the regression is 0.57. As mentioned, the City of Colorado Springs' study defined water application, not as the total water application, but as the irrigation water applied (total water application minus precipitation). Also, the deep percolation was calculated as the total drainage from the lysimeter minus the corresponding percentage due to precipitation. For these reasons, the Gronning Line equation (Eq. 2) is not comparable to CSU equation (Eq. 7).

The CSU research data was modified to make it comparable to the Gronning format by removing precipitation and corresponding drainage component. The results and the Gronning Line are shown in Fig. 7. The equation of the modified CSU regression line is,

$$ND = (0.676 * I) - 0.054 \quad (8)$$

which is essentially similar to the Gronning equation (Eq. 2). Similar to the Cottonwood Curve, the Gronning format is based on practical considerations since it enables the City of Colorado Springs to determine deep percolation solely as a function of irrigation water application. However, the accuracy of the Gronning format is questionable since removal of the precipitation component leads to a distortion of the results. This distortion is observed in the large difference in the x-intercept values for the CSU regression lines using the two water applications formats.

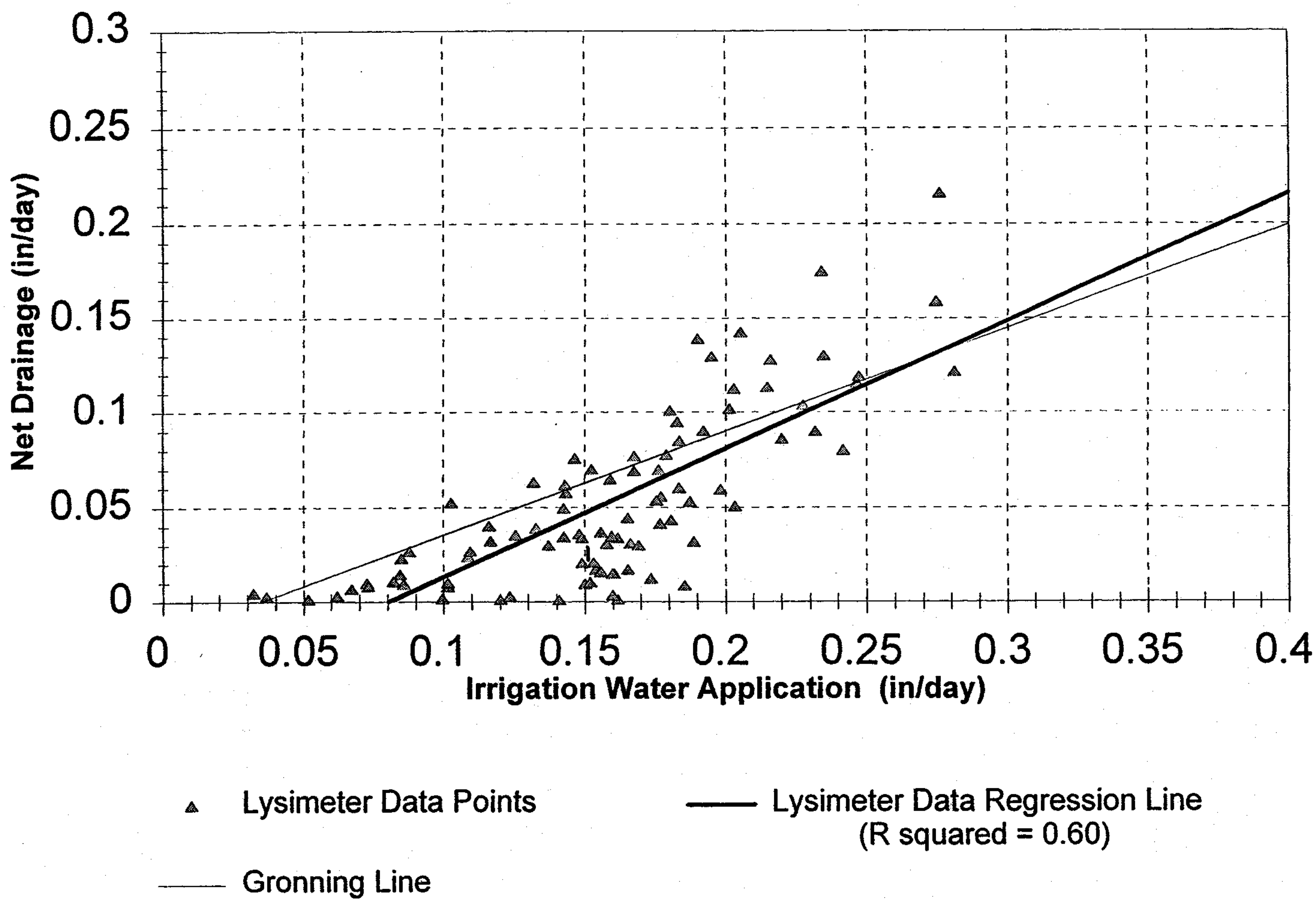


Fig. 6. Gronning Line Compared to CSU Data

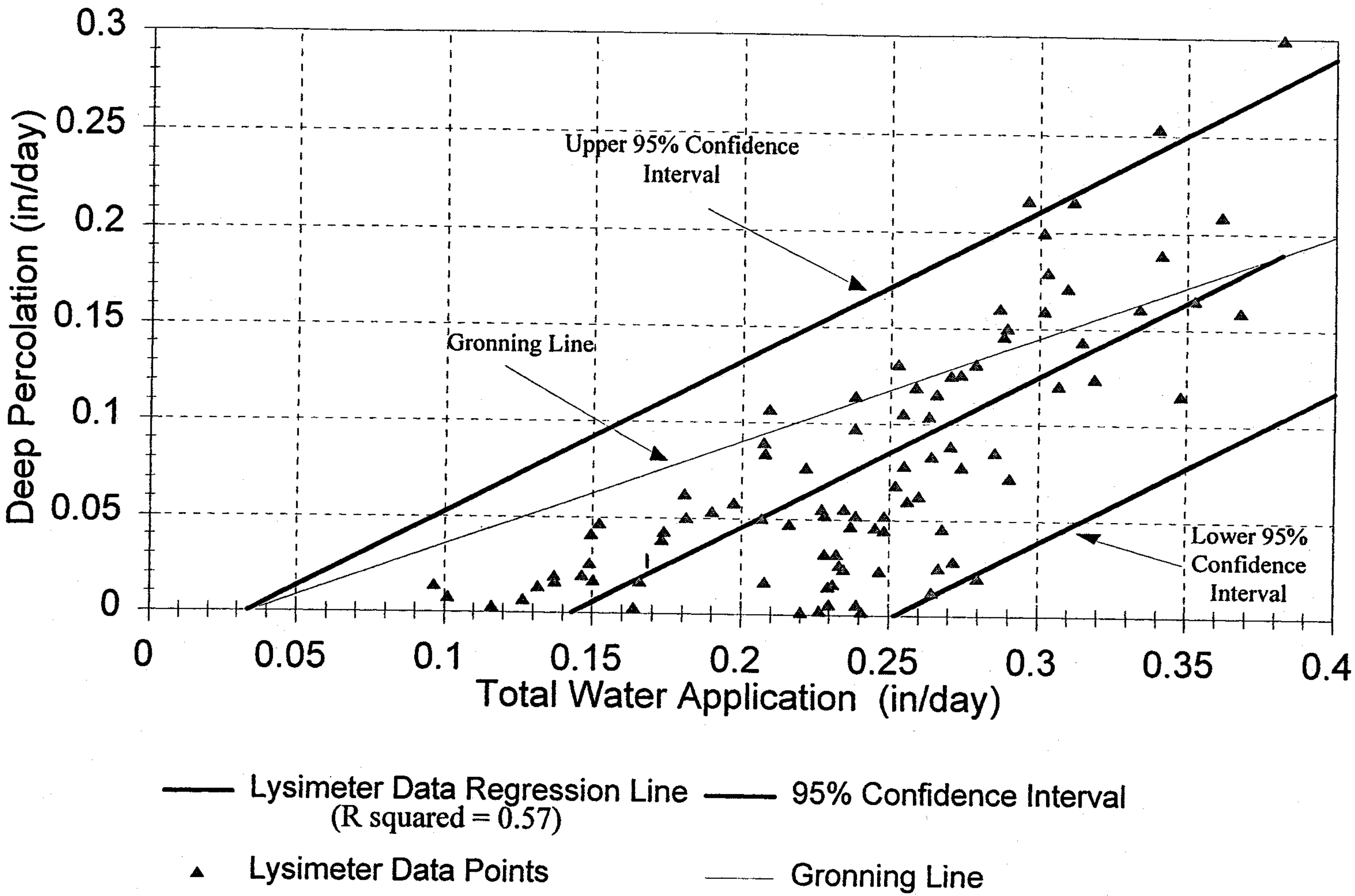


Fig. 7. Gronning Line Compared to Modified CSU Data

RESULTS: EVALUATION OF SMALL LYSIMETERS FOR CONSUMPTIVE USE

Comparison of Standards

Before evaluating the accuracy of small lysimeters with reference to the two standards, the large lysimeter and potential ET calculated from weather data, it is desirable to compare the two standards. Three methods were used to calculate potential ET (ET_0): the 1963 Penman method, Penman-Monteith method, and the SCS Blaney-Criddle method using local crop coefficients for turf grass. The results, and their comparison to the large lysimeter results, are shown in Table 1. The ET_0 comparisons show consistent results between the 1963 Penman and the Blaney-Criddle methods. The Blaney-Criddle results were 3% to 8% lower than the 1963 Penman results in all years except 1994, when the Blaney-Criddle was 2% higher. The Penman-Monteith results were not consistent with the other methods, with substantially lower values.

Table 1. Comparison of seasonal ET_0 and large weighing lysimeter (LWL) ET_a results

June 1 - Sept. 1 **Potential ET (mm)**	**1992**	% Dif. From LWL	**1993**	% Dif.. From LWL	**1994**	% Dif.. From LWL	**1995**	% Dif.. From LWL
1963 Penman	417	+31	447	+59	453	-10	445	-2
Penman-Monteith	317	-1	367	+31	386	-23	376	-17
SCS Blaney-Criddle	403	27	411	+46	464	-8	432	-5

The Penman-Monteith method contains a wind drag factor based on the grass height. For turf grass, as the height of the grass increases, more surface area is exposed to wind, thereby increasing the amount of water vapor transfer and actual ET of the grass (ET_a). In 1992, the grass was cut to its shortest length of the four seasons (5 cm). The Penman-Monteith results were 24% lower than the 1963 Penman results, the maximum difference in all four seasons. In 1994 and 1995, the grass was cut to its longest length (9 cm) and the difference between the two methods was 15% for both years. This trend suggests that for this lysimeter area, as grass height lengthens, the difference between the two methods becomes narrower.

Another factor which may have influenced the Penman-Monteith results is the manner in which the ET_0 was calculated. The Penman-Monteith calculation is "most accurate when used on an hourly basis and the values summed to obtain daily estimates of ET_0" (Jensen *et al.*, 1990). This method was not used for this research, but rather, daily mean weather data values were used to calculate the daily ET_0. The daily values were summed to determine the seasonal total. This modified method was used since the seasonal ET_o values were being compared. Hourly-based calculations are more important when comparing results for shorter periods of time such as days or weeks. The difference in the seasonal results between the two ET_o calculation methods is considered minor.

The results of the large weighing lysimeter compared specially well with the 1963 Penman equation (Fig. 8). In this figure, the Penman ET_o is calculated daily so the line is more smooth than the lysimeter ET_a (actual ET) which is calculated weekly. The results are essentially identical with large lysimeter seasonal ET_a of 454 mm compared to 445 mm calculated by the use of 1963 Penman equation. Based on these findings, it was decided to use the 1963 Penman equation and the large lysimeter as the two reference standards for evaluating the accuracy of small lysimeters.

Comparison of the Small Lysimeter Types

From the measurements of irrigation water, precipitation, change in soil-moisture content and the amount of drainage water, daily and then seasonal ET values were calculated for the two types of small lysimeters (Table 2). Also included in this table are the seasonal ET estimates by the large lysimeter. It should be noted at the outset that the 1993 ET estimates are significantly lower than the corresponding estimates for the other three years. In the 1993 summer season, the amount of water applied to all lysimeters was much lower due to a misunderstanding of the scheduling program. The soil moisture content in lysimeters fell below field capacity and this resulted in lower ET values measured both for the large and small lysimeters in 1993.

An analysis of variance statistical analysis was made to determine if there was a significant difference between the weighing and drainage type small lysimeters with respect to ET_a. Using a threshold p-value equal to 0.05, four-seasons' data indicate that there is no significant difference between the drainage type and weighing type small lysimeters. The only exception to this conclusion was found in the 1992 results, and the inconsistency is due to the large ET_a values for the small drainage lysimeters. The 1992 mean seasonal ET_a for the drainage lysimeters was 441 mm (38% greater than the large weighing lysimeter), compared to 297 mm (7% less) for the small weighing type lysimeters (Table 2). During the first season (1992), the small drainage lysimeters were suspected of having excess runoff during two large rainfall events resulting in reduced percolation response. The 1992 small drainage lysimeter results are therefore considered to be in error, and the remaining three seasons' data indicate that there is no significant difference between the drainage and weighing type small lysimeters.

There was a considerable amount of variability in the ET_a results between lysimeters with the same characteristics. The ET_a standard deviations for a particular lysimeter and soil type ranged from 0 mm to 130 mm in the small drainage lysimeters, and 4 mm to 185 mm for the small weighing lysimeters. Both the 130 mm and 185 mm values, however, occurred in 1992, the first year of the study. The average standard deviation for ET_a, including all soil types and irrigation frequencies, for drainage lysimeters ranged from 30 mm to 66 mm, and 20 mm to 72 mm for the weighing lysimeters. This is a wide range in ET_a variability which makes any subtle differences in results for the different combinations of parameters (lysimeter type, soil type, irrigation frequency)

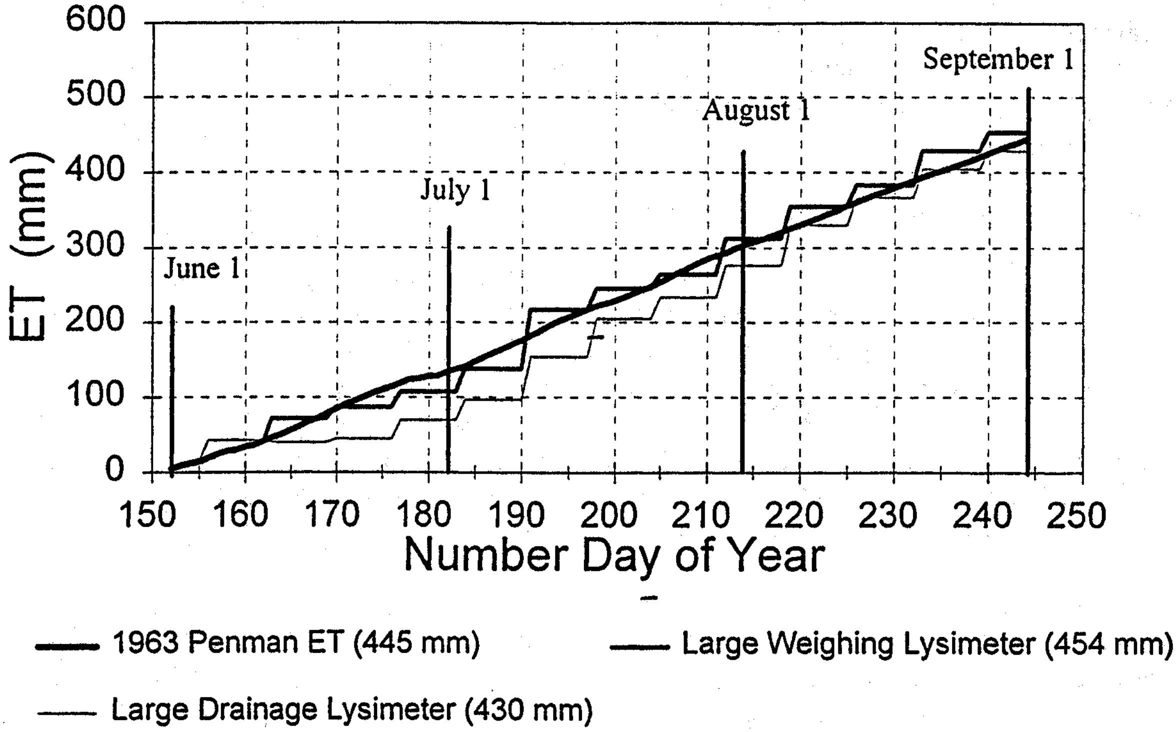


Fig. 8. ET Estimations by 1963 Penman and Large Weighing Lysimeter

Table 2 Mean ET comparison of large vs small lysimeters and soil type

		Drainage Lysimeters		Weighing Lysimeters	
		Mean ET (mm)	% Different From LWL	Mean ET (mm)	% Different From LWL
1992	**Large Weighing Lysimeter**	**319**		**319**	
	FC Loam	**530**	**66%**	**302**	**-5%**
	Clay	472	48%	305	-4%
	Loam	533	67%	409	28%
	Sand	258	-19%	208	-35%
	Small Lysim. Avg	**441**	**38%**	**297**	**-7%**
1993	**Large Weighing Lysimeter**	**281**		**281**	
	FC Loam	**274**	**-2%**	**317**	**13%**
	Clay	354	26%	316	12%
	Loam	271	-4%	311	11%
	Sand	265	-6%	274	-2%
	Small Lysim. Avg	**293**	**4%**	**304**	**8%**
1994	**Large Weighing Lysimeter**	**502**		**502**	
	FC Loam	**502**	**0%**	**455**	**-9%**
	Clay	349	-30%	383	-24%
	Loam	460	-8%	433	-14%
	Sand	327	-35%	374	-25%
	Small Lysim. Avg	**410**	**-18%**	**411**	**-18%**
1995	**Large Weighing Lysimeter**	**454**		**454**	
	Large Drainage Lysimeter	430	-5%		
	5 Irrigations per Week	**486**	**7%**	**521**	**15%**
	3 Irrigations per Week	497	9%	494	9%
	1 Irrigation per Week	423	-7%	405	-11%
	Small Lysim. Avg	**476**	**5%**	**479**	**6%**

very difficult to observe. In order to reduce the influence of a single lysimeter's response and to minimize the lysimeter variability, comparisons between different conditions was based on the mean seasonal ET_a of the two or three lysimeters with the same parameters (Table 2).

Comparison of Small Lysimeters to the Large Lysimeter and the Penman Equation

Any definitive analysis of the accuracy of the small lysimeters compared to the large weighing lysimeter is limited since only one large weighing lysimeter was used during each year of the study. An analysis of variance test to compare small lysimeter types, soil types, and irrigation frequency patterns, was only possible between the small lysimeters. In addition, due to the unique circumstances of equipment problems and under-irrigation, year to year comparisons were not made under the belief that any findings would only confuse or distort the annual results.

The evaluation of the small lysimeter accuracy is made by comparing the seasonal ET_a of the large weighing lysimeter to the small lysimeters with the same attributes, that is, the small lysimeters filled with Fort Collins loam, and in 1995, the small lysimeters irrigated five times per week. The mean seasonal ET_a, based on the two or three small lysimeters with the same soil type and irrigation frequency, was used to make small lysimeter comparisons. The mean seasonal ET_a for the two types of small lysimeters, for each year, is given in Table 2. The mean seasonal ET_as for the drainage lysimeters differ from the large weighing lysimeter by +66% to -2%. If the 1992 drainage lysimeter results are not included, the difference between the large and the small drainage lysimeters is 7% to -2%. The small weighing lysimeters differ from the large weighing lysimeter by +15% to -5%. (The individual lysimeters' seasonal ET_a response differed from the large weighing lysimeter by the following ranges: small drainage lysimeters +66% to -8% (without 1992 results, +24% to -8%; small weighing lysimeters +23% to -15%.)

The results of the seasonal cumulative ET_a comparison between the large weighing lysimeter, Penman Equation and the small lysimeters also indicate that the small lysimeters' ET estimates are similar to the standards (Figure 9). These figures (9.a-9.d for 1992-95 years, respectively) show the cumulative ET for the small lysimeters, large weighing lysimeter, and the 1963 Penman. In all cases, except for the 1992 drainage lysimeters, the large weighing lysimeter's cumulative ET_a line is inside, or very close to, the band of the small lysimeters' cumulative ET_a lines. For the 1993 summer season, Et_a for the large and small lysimeters are significantly lower than the Penman cumulative Et_o because of the deficit irrigation.

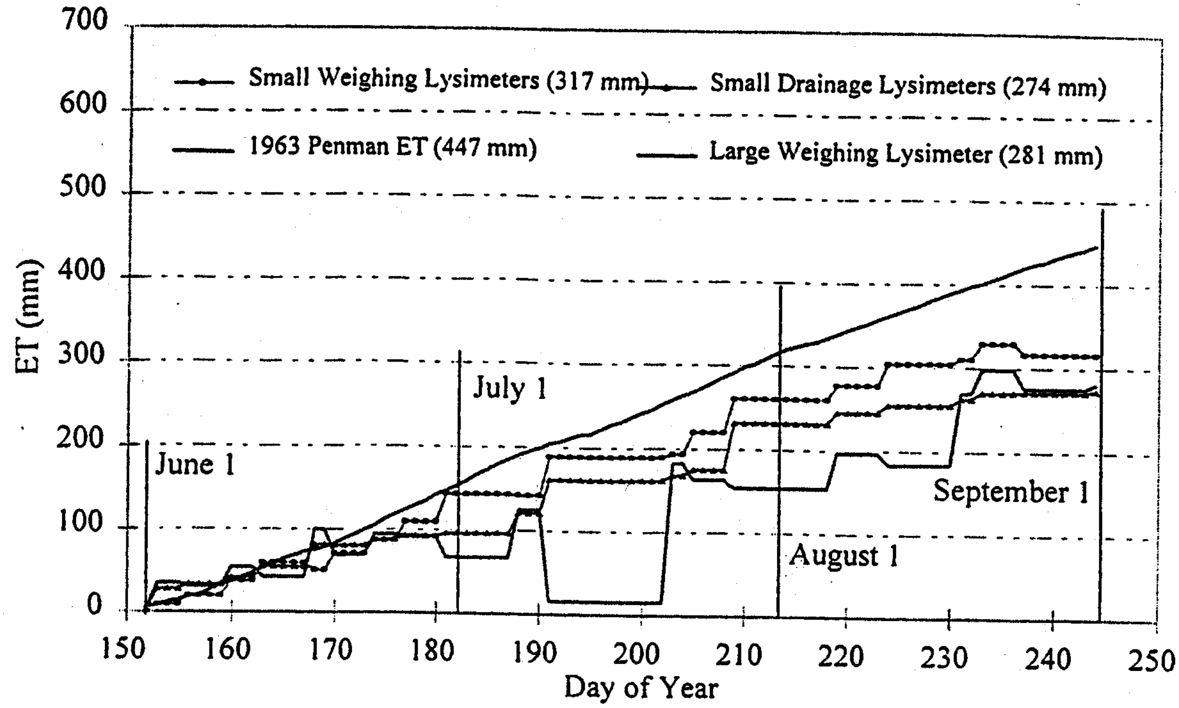


Fig. 9.a. Daily Cumulative ET Measured by Lysimeters and 1963 Penman - 1992 Season.

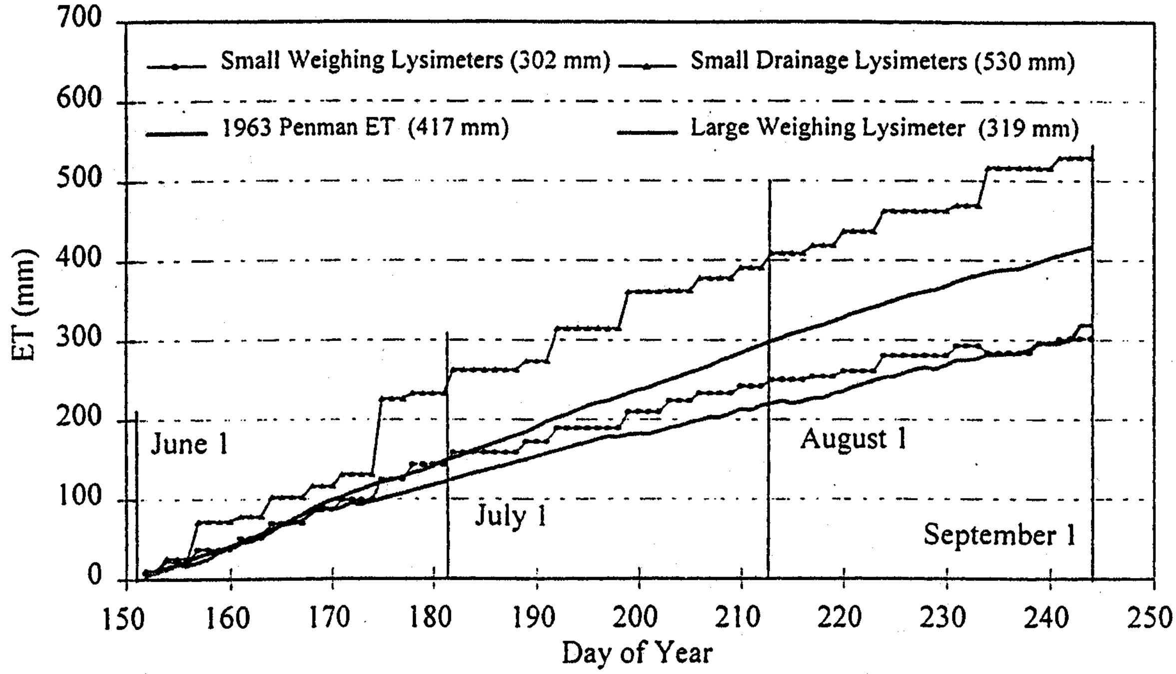


Fig. 9.b. Daily Cumulative ET Measured by Lysimeters and 1963 Penman - 1993 Season.

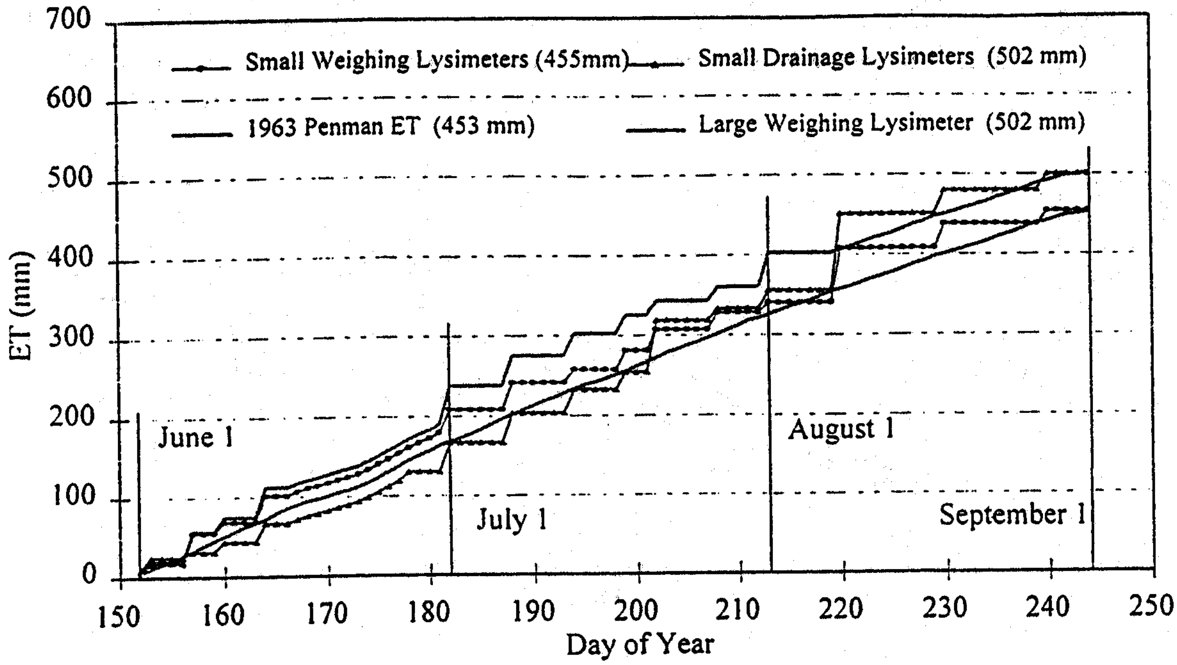


Fig. 9.c. Daily Cumulative ET Measured by Lysimeters and 1963 Penman - 1994 Season.

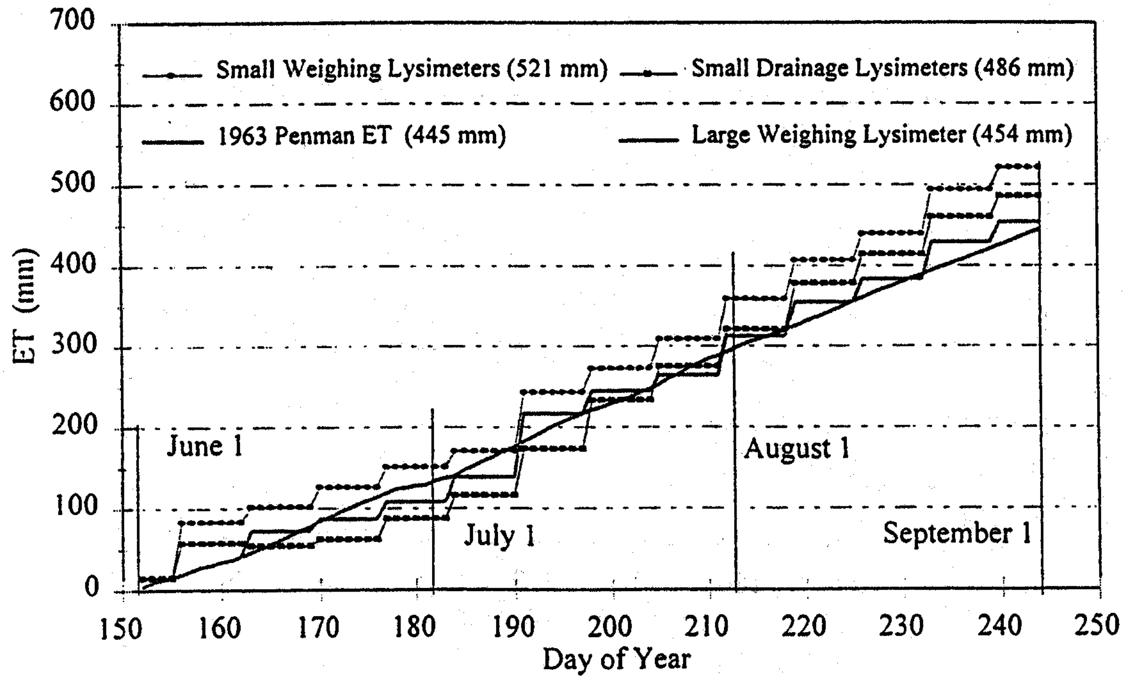


Fig. 9.d. Daily Cumulative ET Measured by Lysimeters and 1963 Penman - 1995 Season.

CONCLUSIONS

As municipalities attempt to meet their continuing water supply demands, return flow water credits from lawn irrigation can be a source of significant financial and water supply benefits. The Cottonwood Curve continues to be the most widely used method for estimating deep percolation in lawn irrigation since it is the result of one of the first lawn irrigation deep percolation studies in the Front Range area, and because it has been accepted by the Colorado Water Court and the Office of the State Engineer. The second major lawn irrigation deep percolation study was performed by the city of Colorado Springs which developed the Gronning Line and the Colorado Springs Polynomial Curve. These representations have also been accepted by the Water Court and the Office of the State Engineer, but their use is almost exclusive to Colorado Springs.

The results of an independent analysis by the Colorado State University show that the two types of small lysimeters (weighing and drainage) compare well with the standard methods of estimating grass consumptive use -- a large lysimeter and the Penman Equation. Also, the two types of small lysimeters are not statistically different from each other. The results imply that the small lysimeters are of acceptable accuracy for estimating grass consumptive use.

With respect to deep percolation, the CSU lysimetry research gave essentially similar results as the linear portion of the Cottonwood Curve and as the Gronning Line. It appears that the small weighing and drainage lysimeters do a satisfactory job of estimating turf grass consumptive use and deep percolation. Due to the unique nature of each study, comparisons among the three studies should be of a more general nature. Both the Cottonwood Curve and the Colorado Springs studies represent a combination of factors including soil types, turf grass quality and people's watering habits. The fact that the CSU and the Cottonwood Curve are almost identical, reinforces the appropriateness of using the Cottonwood Curve for general applications throughout the Front Range.

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