Available online at www.sciencedirect.com
SCIENCE DIRECT®

Computers and Electronics in Agriculture 43 (2004) 55–68

Computers and electronics in agriculture

www.elsevier.com/locate/compag

A volumetric lysimeter system (VLS): an alternative to weighing lysimeters for plant–water relations studies

J.A. Poss [a,*], W.B. Russell [a], P.J. Shouse [a], R.S. Austin [a], S.R. Grattan [b], C.M. Grieve [a], J.H. Lieth [c], L. Zeng [a]

[a] *USDA-ARS George E. Brown, Jr. Salinity Laboratory, 450 W. Big Springs Road, Riverside, CA 92507, USA*
[b] *University of California, Department of Land, Air, and Water Resources, Davis, CA 95616, USA*
[c] *University of California, Department of Environmental Horticulture, Davis, CA 95616, USA*

Received 6 June 2003; received in revised form 5 September 2003; accepted 11 October 2003

Abstract

A closed, recirculating volumetric lysimeter system (VLS) consisting of 24 experimental plant growth units was constructed. The VLS measured irrigation and drainage volumes with pressure transducer trace analysis of irrigation reservoir/sump water elevation. To estimate crop evapotranspiration (ET), changes in soil moisture storage in the plant growth boxes were obtained with neutron probe measurements and were combined with the transducer data to estimate the complete water balance measurement of crop ET. Automated tensiometers, temperature sensors, and four-electrode salinity sensors were installed to monitor soil matric potential, temperature, and electrical conductivity of drainage waters, respectively, 10 times per hour. Plant response to evaporative demand was characterized with a high degree of resolution with the VLS transducer estimated ET detection of approximately 0.1 mm. The VLS provided rapid, reliable, and field-transferable research information. This provided us with the statistical power to compare variables of interest to study the interaction of water quality and quantity on plant ET. Data obtained from the VLS during the cultivation of two crops, alfalfa and tall wheatgrass, under various salinity and water stress treatments were analyzed with a response surface regression model. The model was able to attribute at least 89% of the variation in ET for each crop to salinity and applied water treatments.

Keywords: Alfalfa; Drought; Evapotranspiration; Lysimeter; Salinity; Wheatgrass

* Corresponding author. Tel.: +1-909-369-4863; fax: +1-909-342-4963.
E-mail address: jposs@ussl.ars.usda.gov (J.A. Poss).

0168-1699/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.compag.2003.10.001

1. Introduction

High-resolution data of soil and water dynamics, coupled with measurement of crop response to salinity and water stress, are integral elements to the optimization of efficient irrigation management. Currently, state-of-the-art soil lysimeters that provide weight-based estimates of evapotranspiration (ET) and drainage are used in field situations to monitor crop growth and provide these data. These field systems are a valuable tool for micro-climate optimizations and developing crop coefficients (Piccinni et al., 2002). Such systems provide accurate data when adequate crop buffers and fetch are provided (Howell et al., 1985). Soil lysimeters are generally expensive to install and maintain so that in most field experiments there are few replications (Allen et al., 1998). Hence, replication and treatment combinations are limited and it becomes statistically difficult to evaluate the data these systems generate. The lack of treatment flexibility in the development of an experimental design is a problem when evaluating discrete treatment effects such as crop species or continuous variables such as water or salinity stress. Furthermore, monitoring the response of crops to treatments in large lysimeters installed with field soils requires a long time for the soil water and crop growth parameters to equilibrate with environmental response variables. The main feature of a field lysimeter is that it comes close to mimicking reality yet precise control of all the important variables in this way is difficult and expensive. Monitoring irrigation and drainage water volumes and their respective water qualities, soil moisture storage changes, ET and related crop coefficients, with simultaneous crop response and yield is a daunting task at the field level.

The objective of this study was to modify a sand tank system that would provide an alternative to weighing lysimeters for studying soil–plant–atmosphere interactions associated with salinity and moisture stress. The sand tank system was initially designed as a closed, recirculating system to control soil water salinity through intense leachate management. Through a series of frequent irrigations to eliminate water stress and by optimizing nutrient content in the irrigation water, the sand tank system generated uniform soil salinity profiles to evaluate plant salt tolerance. Under this configuration, this system has proven capable of maintaining highly reliable and accurate soil water salinity profiles for testing a variety of plant species for salinity tolerance, ion interactions, and tolerances to trace elements (Dierig et al., 2003; Ferguson et al., 2002; Grieve et al., 2001; Poss et al., 2000).

In this project, several technical modifications were introduced that allow the system to behave as a lysimeter based on changes in water volumes as opposed to changes in mass.

2. Overview of volumetric lysimeter system (VLS)

2.1. Physical layout

The VLS was composed of 24 sand tanks housed at the USDA-ARS George E. Brown, Jr. Salinity Laboratory in Riverside, CA. Each sand tank consisted of a box (81.5 cm wide × 202.5 cm long × 85 cm deep) with 20 cm-thick concrete walls. The 24 tanks were equally spaced in a 350 m^2 area covered with large aggregate. A corrugated perforated high-density polyethylene drain pipe installed in the concrete-formed trench at the bottom of each tank

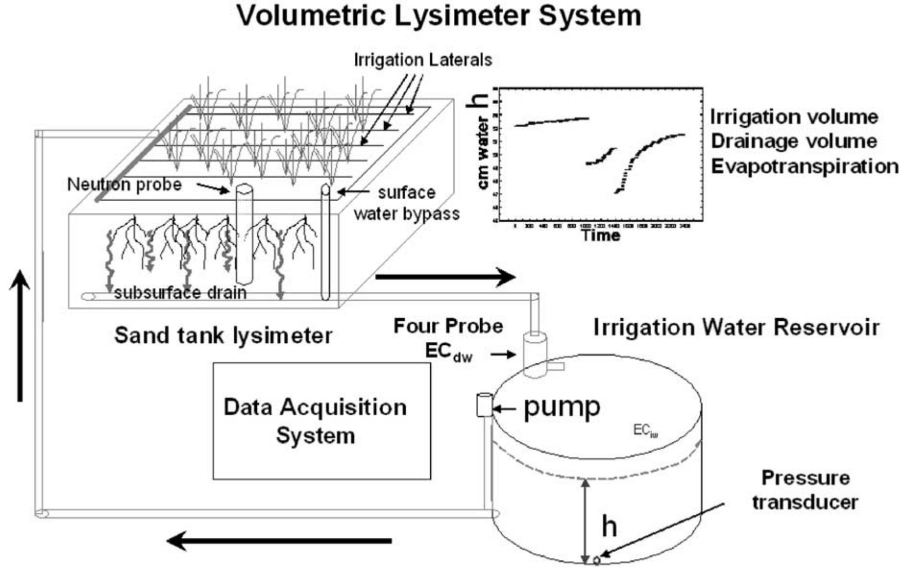

Fig. 1. Diagram of volumetric lysimeter system. By monitoring hydraulic balance with pressure transducers and soil moisture storage changes with neutron monitoring, a system for evaluating plant response to water quality and quantity was developed.

minimized the water table (<5 cm). Each tank was plumbed with 5.1 cm PVC pipes, one for irrigation to the sand tank, and one for return flow to a 1740 l reservoir in the basement below. The lysimeters were filled with sand (particle size distribution ranging from 0.09 to 4 mm) that resulted in a medium with volumetric water content of 0.1–0.3 $cm^3 cm^{-3}$ and similar thermal conductivities and heat capacities as field soil (Wang, 2002). This medium had a high saturated soil hydraulic conductivity (400 cm per day) and provided limited exchange of soil water inorganic constituents with the solid phase, thus simplifying control of soil water chemistry. The modified system was equipped with automated data acquisition of fluid dynamics, temperature, and electrical conductivity (Fig. 1).

As initially designed, the tanks were flood irrigated. Luxurious amounts of irrigation water completely filled the soil profile with excess surface water bypassing through a surface overflow tube (Fig. 1). Excess irrigation water and leachate returned to the reservoirs via gravity flow.

To better simulate field soil moisture conditions, the water delivery system was modified to provide uniform application of small volumes of water and prevent surface water bypass to the drain. This necessitated matching the irrigation rate with the soil hydraulic conductivity to establish a uniform pulse of water that could be applied to the surface. Irrigation uniformity was achieved with a sprinkler network consisting of five 1.9 cm PVC pipes with two rows of 0.16 cm diameter holes offset by 2.5 cm near the apex of the pipe. The modified system applies a very even “film” of irrigation water, delivering approximately 1 cm of water during a 1 min irrigation cycle (about 30 liters per cycle). Irrigations were controlled automatically by an irrigation timer or initiated manually.

Water lost from the system through ET was replenished by adding fresh tap water (City of Riverside municipal water EC $= 0.55\,\text{dS m}^{-1}$) to the reservoirs periodically through the existing automated refill system in the storage reservoirs.

2.2. Data acquisition

A data acquisition system consisting of a datalogger[1] (Campbell model CR23X with AM416 multiplexers; program and schematic diagrams available upon request) was used to measure and record an array of sensors at 6 min intervals. One pressure transducer (Honeywell Microswitch 143PC01D) at each reservoir was used to monitor the pressure head of the available irrigation solution over time. This signal was calibrated to water volume in the reservoir. Analysis of these data allowed calculation of irrigation, drainage, and refill volumes. Transducers (Honeywell Microswitch 143PC15D) were fitted to soil tensiometers (Irrometer Co., Riverside, CA) to monitor soil water matric potential of each sand tank. Temperature data were collected as follows: 12 thermocouples for drainage water temperature correction of electrical conductivity ($F_t = 0.0004\,C^2 - 0.043C + 1.8149$, USDA, 1954) and seven temperature sensors (TC1047AVNBTR Microchip Technology Inc., Chandler, AZ) were used to measure soil temperatures.

The drainage water electrical conductivity was monitored by a four-probe device (Austin and Rhoades, 1979; Rhoades, 1979) placed in a cylindrical well (10 cm diameter × 30 cm deep) housed above the corresponding reservoir and isolated from the reservoir solution before the solution finally drained into the reservoir. Reservoir electrical conductivity was monitored manually with a hand-held meter since changes were small and less variable with time.

2.3. Data processing

Three computer programs were developed to comprise the VLS software. First, *weather* processed local weather station data. Secondly, *neutron* processed volumetric water content data obtained from neutron probe measurements, and finally, *combo* combined *weather*, *neutron*, and additional data collected from the VLS system micrologger to calculate ET and other variables. All programs were developed with Mathematica version 4.2 (Wolfram Research Inc., Champaign Il).

2.3.1. Weather program

Weather processed local weather station data to predict daily ET_0 of a reference crop (i.e., cool-season grass) based on a modified Penman equation (Doorenbos and Pruitt, 1977). The program output weather variables and the Penman values for each Julian day (JD) (Table 1) and retained this information in computer RAM to be used by subsequent programs. The modified Penman method was found to be superior to other ET_0 models for the advective energy conditions present in Riverside, CA (Shouse et al., 1980, 1982). The Penman ET_0-model also compared favorably to a weighing lysimeter cropped to alfalfa in Brawley,

[1] Use of a company or product name is for the convenience of the reader and does not imply endorsement of the product by the USDA to the exclusion of others that may also be suitable.

Table 1
Output of the *weather* program, including the modified Penman equation produced predicted ET for each JD day (JD)

JD	Average temperature (°C)	Average humidity (%)	Average wind speed ($m\,s^{-1}$)	Penman (mm)
35	13.60	31.81	0.82	3.30
36	11.02	27.83	4.58	6.44
37	10.91	15.87	0.72	3.08
38	11.01	17.36	2.22	4.15
39	12.23	40.17	1.00	3.05
40	11.86	44.53	1.02	3.09
41	13.75	20.82	0.98	3.86
42	12.47	49.90	1.38	2.12
43	13.14	79.20	1.96	1.41
44	13.22	95.15	0.60	0.74
45	15.37	77.92	1.06	2.27

CA (R.A. Hutmaker, personal communication). Allen et al. (1998) confirmed overestimation of the modified Penman and stated that variable performance for different methods depended on local conditions. Under advective energy conditions common in southern California, a bias toward overestimation allows the modified Penman model to be applied. When the crop canopy was cut short (recently harvested), the ET values of well-watered treatments compared favorably with the modified Penman model. As a preliminary tool, we chose to use the locally-verified ET_0 model rather than the standard global approach that has not yet been verified for our unique microclimate.

2.3.2. *Neutron program*

The *neutron* program averaged the volumetric water content (θ_v) of each plant growth box. The data were read from an Excel worksheet by Mathematica Link-To-Excel software. The program averaged the soil θ_v over depths of 15, 45, and 65 cm from the surface and added the corresponding JD. The output from *neutron* was used by *combo* (Section 2.3.3) to correct for soil moisture storage changes as follows: for each measured ETpi, the nearest bracketing neutron probe data were used. The specific Julian days (JD) and θ_v values that defined the beginning and the end of the bracket interval were documented (JDbeg./$\theta_v$beg., JDend/$\theta_v$end, Table 2). The difference in water content between the bracket extrema was then interpolated (NPdel, Table 2), if necessary, and subtracted from the ETpi value measured by the VLS to obtain the corrected ET (VLSET, Table 2).

2.3.3. *Combo program*

Combo designated the initiation of each interval by detecting a sudden change in the reservoir depth indirectly with a pressure transducer during either a refill or irrigation event (Fig. 2A). Depth readings reflected ET losses provided that depth changes resulting from irrigation events and refill events were monitored and recorded. Evapotranspiration events were accounted for by allowing maximum drainage before a depth reading was taken. The end of an interval (1 or more days) was determined by experimental protocol related to the frequency of irrigation required for a given soil moisture storage potential and meeting the

Table 2
Tabular data including neutron corrected ET (VLSET), interpolated change in soil moisture storage (NPdel), beginning Julian day/soil volumetric water content (JDbeg./$\theta_v$beg.), ending Julian day/soil volumetric water content (JDend/$\theta_v$end) measured ET per interval (ETpi), cumulative irrigation (CumIrr), drainage volumes (Drainvol), predicted modified Penman ET per interval (PENpi), regressions of measured ET over selected ET intervals (RegETpi), averages of predicted ET over selected intervals (AvgPENpi), cumulative refill (CumRef), crop coefficient per interval(Kpi), leaching fraction (LF), volume based ET per interval (Etpi, l), and time for successive irrigation events required to maintain prescribed ET treatments (IrrTm)

	JD		
	36	38	41
VLSET (mm)	4.0	9.7	10.6
NPdel (mm)	9.7	−1.8	−4.4
JDbeg./$\theta_v$beg. (cm)	34/9.92	36/10.89	36/10.89
JDend/$\theta_v$end (cm)	36/10.89	41/10.45	41/10.45
ETpi (mm)	13.7	7.9	6.2
CumIrr (l)	23.5	55.9	49.7
Drainvol (l)	0.814	42.8	39.4
PENpi (mm)	9.7	7.2	10.0
RegETpi (mm)	8.7	8.7	8.7
AvgPENpi (mm)	9.0	9.0	9.0
CumRef (mm)	28.6	0	0
Kpi	1.41	1.09	0.62
RKpi	0.96	0.96	0.96
LF	0.03	0.77	0.79
ETpi (l)	22.7	13.1	10.3
IrrTm (s)	33.1	19.1	15.0

criteria of complete drainage. For the methods-testing experiment, the crop was irrigated 3 days per week (M, W, F). The depth reading was tabulated just prior to the next irrigation or refill event. This procedure (i.e., recording the depth prior to any detected irrigation event) produced a table of values that included the Julian day (Fig. 2A). The JD was used to create another table (Fig. 2B) as follows: the first depth taken for each JD was tabulated. The time between successive JDs in this table represented intervals defined by triggering events. The difference between depth readings of adjacent JDs in turn produced output of measured ET readings, *per interval* (Figs. 2C and 3, measET). To calculate a given ETpi interval, it was necessary to have two irrigation events as a minimum included in the input file. Since the initial interval was unreliable, data leading and trailing the data of interest were included in the input file.

The irrigation events were detected by monitoring any *negative* change in the reservoir water volume, below a given criterion. If the datalogger sampled during an irrigation or refill event, an anomaly might have developed as follows: the datalogger sampled during the irrigation or refill event that resulted in an intermediate point between the true pre- and post-event datapoints. To guard against this, the actual values used to create the final tables were obtained as follows: the pre-event datapoint was replaced by the point *prior* to it. By the same argument, the post-datapoint was replaced by the datapoint following it (Fig. 2D). The difference (in mm) between the previous and post-depth readings after three logging intervals (an irrigation event occurs well within the logging interval of 6 min) was posted

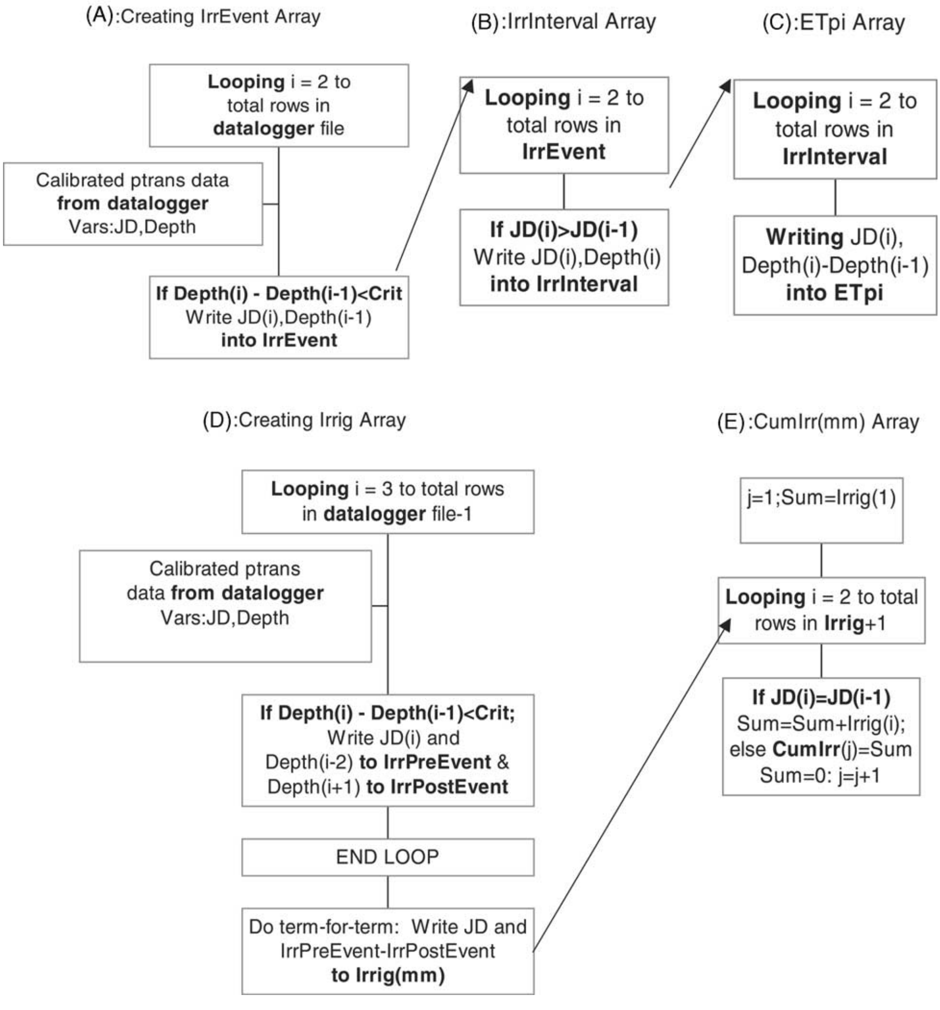

Fig. 2. Flowchart describing the sequence of programming steps to evaluate VLS pressure transducer water depth traces. The sequence led to the ETpi and irrigation amounts for each reservoir for a given JD interval.

as “Irrig” (Fig. 3) at the end of the protocol interval. The sum (in mm) of all the irrigation events (Fig. 2E) in an ET interval, was posted as “CumIrr” (Fig. 3). This value, multiplied by the sand tank surface area (1.65 m^2), measured the cumulative amount of water (in liters) per interval (Table 2) for comparison with water meter data.

After substantial ET occurred, occasional additions of make-up water were required to maintain the volume and salinity concentrations of the VLS and keep the irrigation pumps primed. The refill events were represented in the data by *positive* changes in successive depth readings above the given criterion. The cumulative difference (mm) between the depth readings prior to, and after the refill events per interval was posted as CumRef (Fig. 3, Table 2).

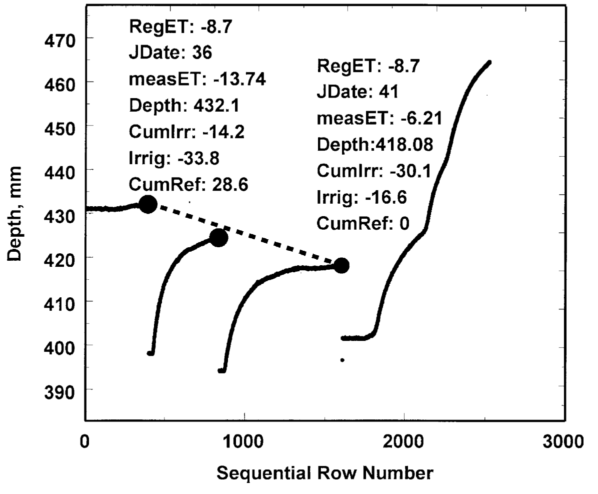

Fig. 3. Portion of the trace of reservoir water depth readings adjusted to equivalent sand tank water depths. The measured ET (mm), denoted with closed circles, appears on the right edge of the corresponding interval. The dashed line marks a regression of the measured ET interval. (meas ET: VLS measured ET; Jdate: Julian day; RegET: Linear regression of ET per interval; Depth: depth of water in irrigation reservoir; CumIrr: sum of all the irrigation events per ET interval; CumRef: cumulative difference between the depth readings prior to and after the refill events per interval. Note sudden rise in reservoir volume after JD 41 due to rain capture.

For historical and interpolative VLS capabilities for ET events, linear regression techniques were employed. The linear regression of ET per interval (RegET, Fig. 3, and RegETpi, Table 2) was created on a sub-interval of the IrrInterval array (Fig. 2B). The sub-interval contained those JD whose corresponding depth readings were monotonically decreasing within a given tolerance. The regressed value was displayed (Fig. 3, label RegET) above each JD contained in the sub-interval used in the regression. For comparison, the JDs in the sub-interval were used to obtain corresponding averaged ET_0 values AvgPENpi (Fig. 4, Table 2).

The measured ET loss (Fig. 4, “measET”) per interval for each sand tank was compared with the ET_0 estimated with the modified Penman *per interval* in graphical and tabular form (Fig. 4, Table 2). For JD 41, the estimated Penman ET_0 value per interval (“PENpi”, Fig. 4) of 10.0 mm (PENpi, Table 2) represents the sum of Penman values from *Weather* for JDs 39,40,and 41 (Table 1). The average Penman ET_0 value (regression interval JDs 36 through 41) was 9.0 mm (Table 2, Fig. 4; “AvgPENpi”). The average Penman ET_0 was compared to the regressed measured ET (“RegET”, Fig. 4).

A crop coefficient for a given interval (Kpi, Table 2) was calculated as the ratio of the measured ETpi to the estimated ET(PENpi). Similarly, RKpi was calculated as the ratio of the regression value for a given interval (RegETpi) to the average estimated ET_0 (AvgPENpi). The measured ET, in liters, (ETpi, l), Table 2) was found by multiplying the measured ET, in mm, (row label ETpi) by the area of the sand tank. The drainage volume (Drainvol, Table 2) was found by taking the difference between the cumulative irrigation (CumIrr, Table 2) and the measured ETpi (l). The leaching fraction (LF, Table 2) was the ratio of the drainage volume to the cumulative irrigation volumes, which are, for the

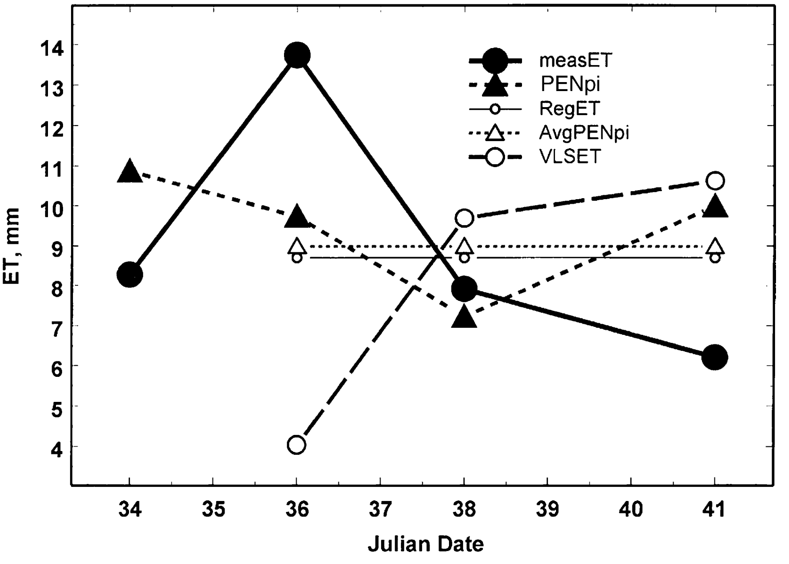

Fig. 4. Plot of measured (measET) and estimated ET_0 (PENpi) and average estimated ET_0 based on Penman equation (AvgPENpi) over the same time interval used in regression calculations (RegET) based upon measured data, and the θ_v storage corrected ET (VLSET).

most part, equal to the cumulative infiltration volumes since no water was lost from the system except through ET. The amount of time required to irrigate any given sand tank was calculated by dividing the measured ET, in liters, by the volumetric flow rate ($l\,s^{-1}$) of the pump servicing the sand tank. The rates of irrigation needed to establish the water treatments were determined with the *Combo* program by measuring the total millimeters of water consumed by the control VLS treatments for each species separately ($EC = 3\,dS\,m^{-1}$, 1.25 ET ratio) and then calculating the time (s) each pump needed to operate at a calibrated flow rate ($l\,s^{-1}$) to deliver this volume for the specified ET ratio in the remaining 22 VLS experimental units (IrrTm, Table 2).

2.4. VLS calibration

The volume of applied water measured by the *Combo* program with pressure transducer technology was verified with an independent water meter refill system. For each of the 24 VLS units, three replications of added volumes were checked. Refill volumes were measured with a digital-output water meter triggered to shut off through the use of a level sensor switch to determine when the reservoir was filled to volume. During each refill event, the water meter independently measured the volume that was also measured by the VLS transducer apparatus. For the relationship between the pressure transducers and the water meter, the deviation from the one-to-one line was significant based on a *t*-test due to the inaccuracy of the water meter pulse counter factor. As greater volumes of water were added, the overestimation of the volume by the meters increased. Despite this error the relationship is within the 95% confidence interval for one-to-one correspondence (Fig. 5)

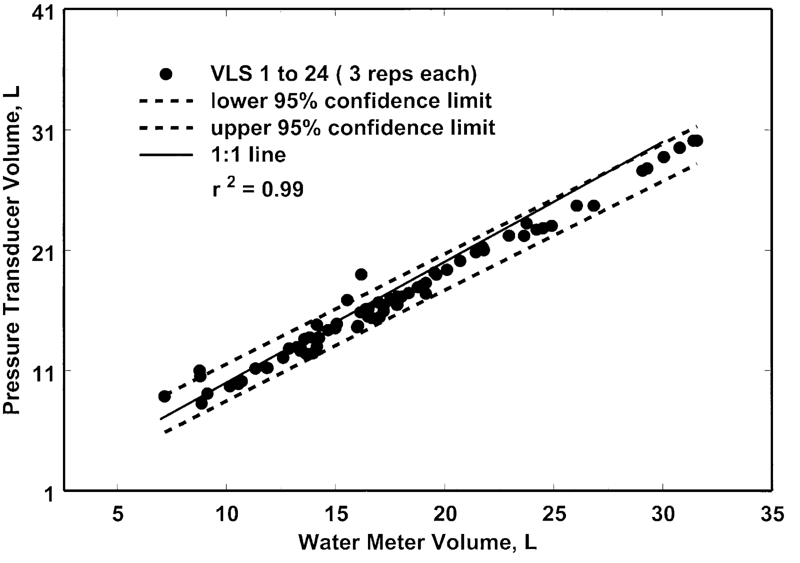

Fig. 5. Calibration of pressure transducers with water meter determined volumes measured in the 24 VLS reservoirs (3 volumes per replicates per reservoir).

for refill volumes less than approximately 40 l. Furthermore, the transducers appeared to equal or exceed the accuracy of the water meter measurement. The resolution of transducer estimated volume translates to an ET detection of approximately 0.1 mm.

To manipulate for experimental purposes the target ET ratio or volumes of applied water relative to some baseline evaporative demand, the ET target that was measured with the water meter was also compared with ratios measured with the VLS. The VLS was able to target different volumes of applied water for wheatgrass (Fig. 6A) and alfalfa (Fig. 6B) crops over a large range of actual ET ratios with a linear correlation that accounted for greater than 98% of the variation in the ET measurements.

3. Application of the VLS

3.1. Measuring alfalfa and tall wheatgrass ET under salinity and water stress

The effects of six salinity treatments ($EC_{iw} = 3, 8, 13, 18, 23$, and $28\,dS\,m^{-1}$) on ET of “Salado” alfalfa (*Medicago sativa* L.) and “Jose” tall wheatgrass (*Agropyron elongatum* L.) were determined in the VLS. Four different irrigation regimes, determined independently for each species, were based on ratios of measured ET of the high irrigation volume, low salinity control treatment. Ratios of the control ET were then applied at 0.5, 0.75, 1.0, and 1.25 times the amount consumed by the control treatments with the system as previously described.

The experiment was a partial-factorial experimental design with no replication to evaluate the effects of salinity and water application on ET of two field crops over a period of one cutting cycle. Of the 24 VLS units, half were used to grow alfalfa and half to grow tall

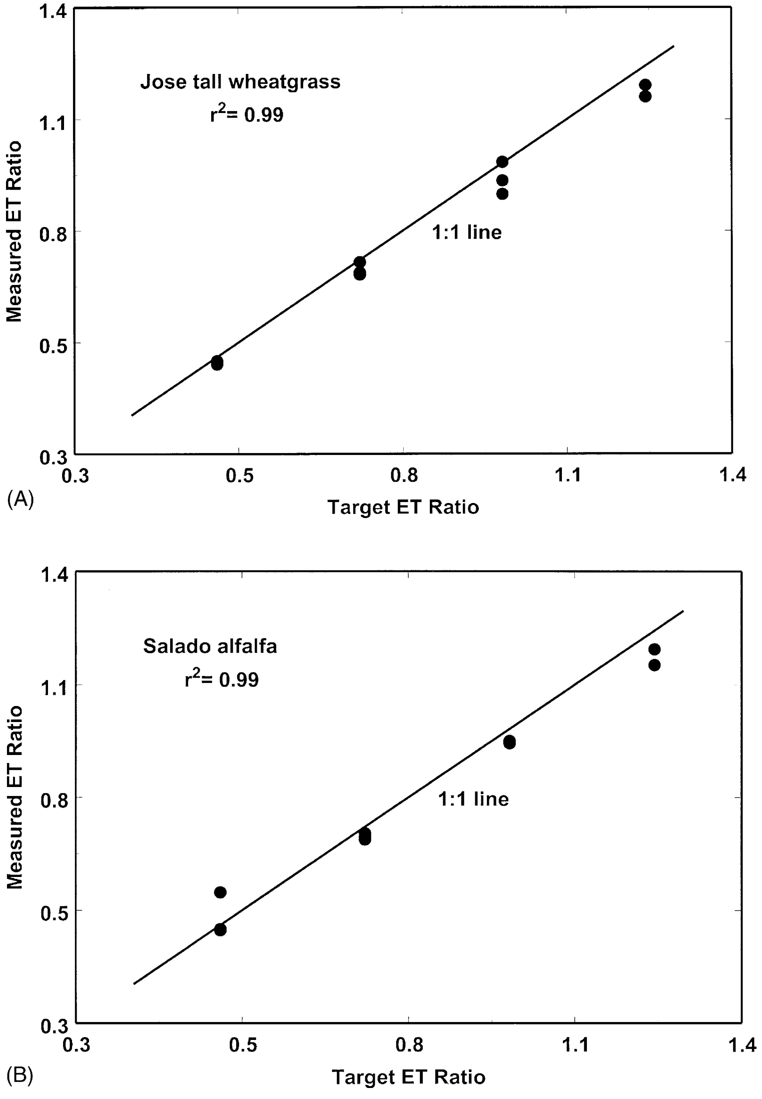

Fig. 6. Relationship between target ET ratios obtained with VLS for tall wheatgrass and alfalfa. The ET target was measured with the water meter.

wheatgrass. Of the 24 potential treatment combinations, a grid of treatments was determined to orthogonally space salinity and water application treatments over the desired ranges for each species with half of the combinations.

After several cuttings and uniform salinity profiles were established with adequate irrigation, water stress was then imposed immediately after a subsequent cutting and measured during September 2002. Treatment effects on crop ET from the first and second cutting after 40 days of simultaneous salinity and water stress were measured with the VLS.

The data analysis incorporated the use of a quadratic response model for the crop ET variable that was expressed as:

$$\mathrm{ET} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_1^2 + \beta_5 x_1 x_2 + \varepsilon \quad (1)$$

where x_1 and x_2 represent varying salinity and ET ratios, respectively, and ε is experimental error. The coefficients (β_0, β_1,...) were established for the particular variable as part

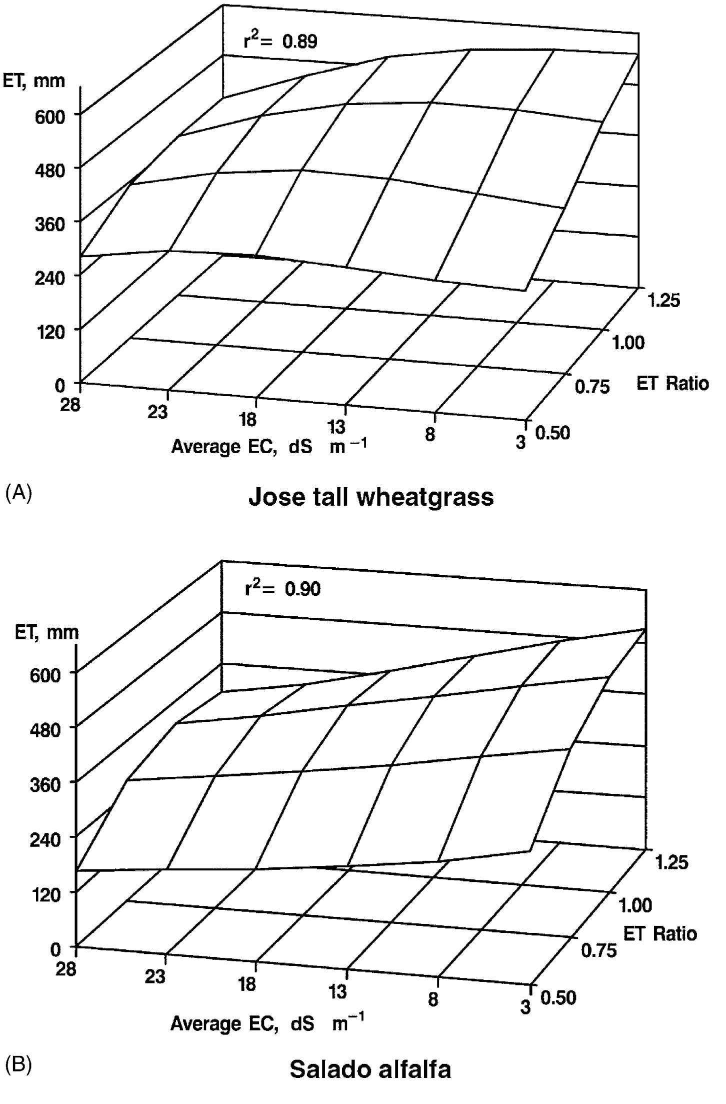

Fig. 7. Predicted ET (VLSET, mm) of tall wheatgrass and alfalfa crops growing under simultaneous water stress for 40 days in pre-salinized soil profiles. Regression statistics were based on ratios, and salinities measured with VLS.

of the regression analysis, and statistics including surface means, correlation coefficients, coefficients of variation, and predicted surfaces were generated (RSREG procedure, SAS, 1997).

3.2. Experimental results

The input ET data for the surface regression was the sum of the VLSET over the interval of interest. The salinity input was the average of the drainage water from the VLS well four-probe and the irrigation water electrical conductivity in the reservoir measured several times per week. Input for ET ratio was the actual target ET measured by the VLS. Both crops were significantly influenced by water application (ET ratio, $P > F = 0.01$) and the average salinity ($P > F = 0.02$) the crops were exposed to. Predictive surface regression statistics for wheatgrass (Fig. 7A) indicated that maximum ET rates were found at 1.20 times the baseline ET measured in the well-watered control treatment where average soil water salinity was 10.4 dS m^{-1} with a surface (treatment) average ET of 391 mm. For alfalfa (Fig. 7B), the cumulative ET surface regression indicated that maximum rates were at 1.02 times the baseline ET measured in the well-watered control treatment where average soil water salinity was 4.8 dS m^{-1} with a response surface average ET of 318 mm.

The power of the linear regression feature in *combo* was illustrated when data were collected over many days and *combo* calculated the dramatic differences in ET. For example, a substantially lower ETpi slope value for wheatgrass grown with 23 dS m^{-1} water quality (8.7 mm for a 4-day interval) was found in contrast to the non-saline control (16.7 mm per 4-day interval) when equivalent irrigation volumes were applied.

4. Conclusion

The VLS design described here has a number of advantages over weighing lysimeters. The ability to instrument a large number of experimental units provides greater latitude for quantifying the response of plants to varying water quality and irrigation application rates. The simultaneous monitoring of electrical conductivity, soil matric potential, temperature, water applications, ET requirements for the crop, and resulting drainage patterns provides a very robust system with a high degree of control and resolution. Accurate quantification of these variables will improve our understanding of crop response to combined salinity and water stress, an area of research that has been largely neglected over the years. This neglect is presumably due to inadequate methodologies to simultaneously characterize these two important plant stresses. Research of this nature will eventually provide valuable insights into whether the plant responds equally to the combined matric and osmotic potentials or whether one parameter must weigh more heavily than the other.

Acknowledgements

This work was funded by California Department of Water Resources CALFED grant. The authors thank Debra Gonzalez, project manager, for her guidance in the completion of this work. The authors also extend their gratitude to Jack Jobes, JoAn Fargerlund, Doug Diaz, Kathy Kim, Larry Polk, and Erin Wagner for their efforts in constructing and monitoring the VLS.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evaporation:guidelines for computing crop water requirements. Irrigation and Drainage Paper 56. U.N. Food and Agriculture Organization, Rome, 300 pp.

Austin, R.S., Rhoades, J.D., 1979. A compact, low-cost circuit for reading four-electrode salinity sensors. Soil Science Society of America Journal 43, 808–810.

Dierig, D.A., Grieve, C.M., Shannon, M.C., 2003. Selection of salt tolerance in *Lesquerella fendleri* (Gray) S. Wats. Industrial Crops and Products 17, 15–22.

Doorenbos, J., Pruitt, W. O., 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24. U.N. Food and Agriculture Organization, Rome, 144 p.

Ferguson, L., Poss, J.A., Grattan, S.R., Grieve, C.M., Wang, D., Wilson, C., Donovan, T.J., Chao, T., 2002. Pistachio rootstocks influence scion growth and ion relations under salinity and boron stress. Journal of American Society of Horticultura Science 127, 194–199.

Grieve, C.M., Shannon, M.C., Poss, J.A., 2001. Mineral nutrition of leafy vegetable crops irrigated with saline drainage water. Journal of Vegetable Crop Production 7, 37–47.

Howell, T.A., McCormick, R.L., Phene, C.J., 1985. Design and installation of large weighing lysimeters. Transactions ASAE 28, 106–112.

Piccinni, G., Marek, T., Jett, M., Schneider, A., Dusek, D., Howell, T., 2002. Construction of three weighing lysimeters for the determination of crop coefficients for improving water use efficiency and managing irrigation of row and vegetable crops in the winter garden. Texas A&M Agricultural Research & Extension Center at Uvalde. Bulletin: UREC-02-019.

Poss, J.A., Grattan, S.R., Suarez, D.L., Grieve, C.M., 2000. Stable carbon isotope discrimination: an indicator of cumulative salinity and boron stress in *Eucalyptus camaldulensis*. Tree Physiology 20, 1121–1127.

Rhoades, J.D., 1979. Inexpensive four-electrode probe for monitoring soil salinity. Soil Science Society of America Journal 43, 817–818.

SAS Institute Inc., 1997. SAS/STAT software: changes and enhancements through release 6.12. SAS Institute Cary, NC.

Shouse, P.J., Jury, W.A., Stolzy, L.H., 1980. Use of deterministic and empirical models to predict potential evapotranspiration in an advective environment. Agronomy Journal 72, 994–998.

Shouse, P.J., Jury, W.A., Stolzy, L.H., Dasberg, S., 1982. Field measurement and modeling of cowpea water use and yield under stressed and well-watered growth conditions. Hilgardia 50, 1–24.

USDA Handbook 60: Diagnosis and Improvement of Saline and Alkali Soils, 1954. United States Salinity Laboratory Staff. U.S. Government Printing Office, 160 pp.

Wang, D., 2002. Dynamics of soil water and temperature in aboveground sand cultures used for screening plant salt tolerance. Soil Science Society of America Journal 66, 1484–1491.