REAL−TIME MEASUREMENT OF DRAINAGE FROM POT−IN−POT CONTAINER NURSERIES

H. Zhu, C. R. Krause, R. C. Derksen, R. D. Brazee, R. Zondag, N. R. Fausey

ABSTRACT. *In pot−in−pot nursery production, information on the amount of drainage water loss from the pots due to irrigation and rainfall is beneficial to improving irrigation water use efficiency and optimizing nutrition management. An experimental field site was established to determine drainage water loss from pot−in−pot container nurseries with micro−irrigation. The site consisted of 50 container−grown trees, 10 tipping−bucket rain gauge units, and a portable weather station. Rain gauge units were calibrated four different ways to determine repeatability and reliability for real−time measurement of the drainage water. Volume of water was calculated from the product of number of tips and volume per tip. Accuracy of measurements was verified by the amount of drainage water collected weekly in collection buckets located under rain gauge units for various irrigation applications and rainfall events. The maximum difference in the weekly amount of drainage water collected with the collection buckets and measured with the rain gauge units was 1.215 L (or 5.3% error) when the daily irrigation application to five trees was 15.5 L. The system reported real−time measurement of drainage water due to irrigation and rainfall, and provided a research tool to evaluate strategies for nurseries to better manage irrigation schedules.*

Keywords. *Irrigation, Rainfall, Rain gauge, Tipping bucket, Tree production, Water management.*

In nurseries, the pot−in−pot system of production has been expanding rapidly during the past decade. In this system, each container−grown plant is placed inside an outer socket container that is permanently placed in the ground. Advantages of using the pot−in−pot system are: it can moderate root temperature and improve root quality by protecting trees from root−killing heat on container side walls during the summer and extreme temperature changes during the winter; it can help prevent the blowing over of container−grown trees; and it can reduce harvesting labor cost compared to field−grown tree production. Conversely, the disadvantage of the pot−in−pot system is that it restricts root spread for uptake of nutrients and water.

To compensate for the disadvantage, it is essential to apply sufficient water two or more times throughout a day and supplemental nutrients to sustain the rapid growth of trees (Beeson and Gilman, 1995; Ruter, 1997; Beeson and Keller, 2003). However, these irrigation and fertilization practices have raised concerns over water use efficiency because of drainage water loss through the containers and the extent of nutrient and chemical leaching with the drainage water to the soil and groundwater. Improving irrigation management in pot−in−pot production is limited because drainage water loss through the in−ground containers cannot be directly observed during irrigation. To obtain high water use efficiency and to implement automatic irrigation control, it is important to know how much water can be applied to each container before drainage begins. Therefore, a method to determine drainage water loss for pot−in−pot nursery production is needed.

Large tipping buckets have been widely used to measure surface water runoff and subsurface drainage in farm fields for many years (Johnston, 1942; Bentz and Amerman, 1968; Hanna, 1995; Khan and Ong, 1997). Edwards et al. (1974) detailed theoretical and experimental design considerations and error sources for large−capacity tipping buckets used to measure drainage and runoff. Since a tipping bucket requires mechanical action, its tipping rate varies with flow rate due to surface tension effects and friction in the pivot support. Volume per tip at very low tipping rates is usually constant, but it changes at high tipping rates, and the number of tips varies nonlinearly with flow rate (Brakensiek et al., 1979; Barfield and Hirschi, 1986; Zhao et al., 2001). The relative error could be significant even with low flow (Yu et al., 1997). Methods to correct the error due to flow rate variation depend on application conditions. For example, Barfield and Hirschi (1986) used a power function regression equation to correct errors, while Khan and Ong (1997) used a linear regression equation to correlate runoff flow rate with tipping rate.

Continuous flow measurement methods, including flumes (Meyer and McCune, 1958) and drop box weirs (Lenz, 1943; Johnson et al., 1966), have been used to measure flow rate and volume for drainage and runoff, but the accuracy of these methods is very low (Barfield and Hirschi, 1986).

Article was submitted for review in February 2004; approved for publication by the Soil & Water of ASAE in October 2004.

The authors are **Heping Zhu, ASAE Member Engineer,** Agricultural Engineer, **Charles R. Krause,** Research Plant Pathologist, **Richard C. Derksen, ASAE Member Engineer,** Agricultural Engineer, and **Ross D. Brazee, ASAE Member Engineer,** Senior Research Scientist, USDA−ARS Application Technology Research Unit, Wooster, Ohio; **Randall H. Zondag,** Commercial Horticultural Agent and Chair, The Ohio State University Extension, Lake County, Ohio; and **Norman R. Fausey,** Soil Scientist, USDA−ARS Soil Drainage Research Unit, Columbus, Ohio. **Corresponding author:** Heping Zhu, USDA−ARS Application Technology Research Unit, Agricultural Engineering Building, OARDC, 1680 Madison Ave., Wooster, OH 44691; phone: 330−263−3871; fax: 330−263−3670; e−mail: zhu.16@osu.edu.

Compared with conditions in fields, the pot−in−pot system requires complex production practices due to the various types of media, species, and irrigation schedules. Micro−irrigation is commonly used in pot−in−pot container nurseries. The amount of drainage water loss from a container due to irrigation is relatively low, but the amount could be considerably higher due to intensive rainfall. There are no inexpensive electronic flow meters available for such a variable, normally very low flow measurement. Small tipping buckets show promise as a suitable method for this application.

The objective of this research was to develop an instrument system using rain gauge units containing small tipping buckets to determine the amount of water draining from pot−in−pot containers in real time, and develop a non−linear equation to correlate the amount of drainage water and tipping rates from the small tipping−bucket rain gauges.

MATERIALS AND METHODS

An experimental field system (fig. 1) to measure drainage water from pot−in−pot nursery container production was established in a commercial nursery field. The system mainly consisted of 50 pot−in−pot tree containers with micro−irrigation, 10 drainage water measurement devices, and a portable weather station. The containers with trees were arranged in

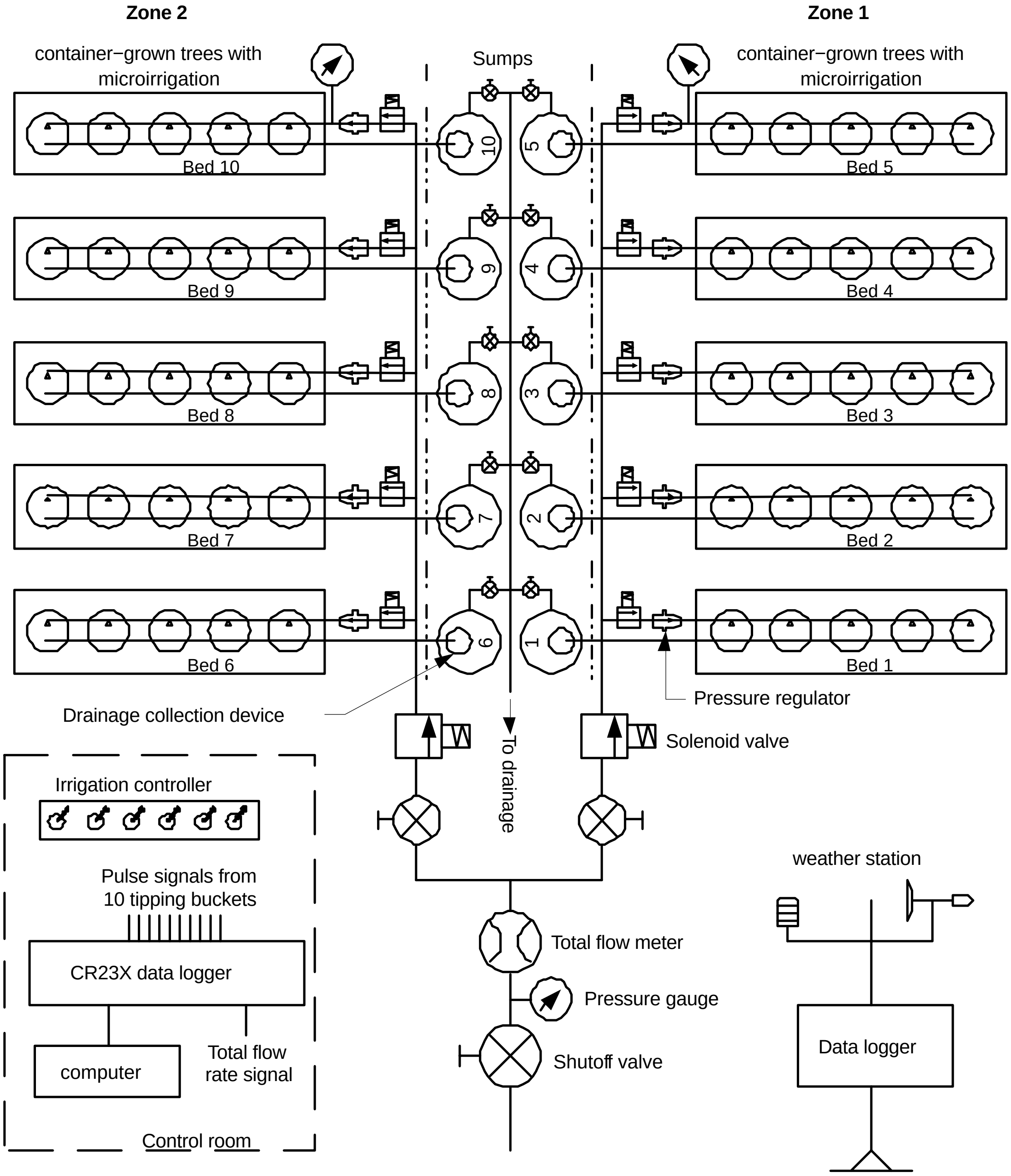

Figure 1. An experimental field plot containing 50 container−grown trees with micro−irrigation, 10 drainage measurement devices, and a portable weather station to measure drainage water from the pot−in−pot production system.

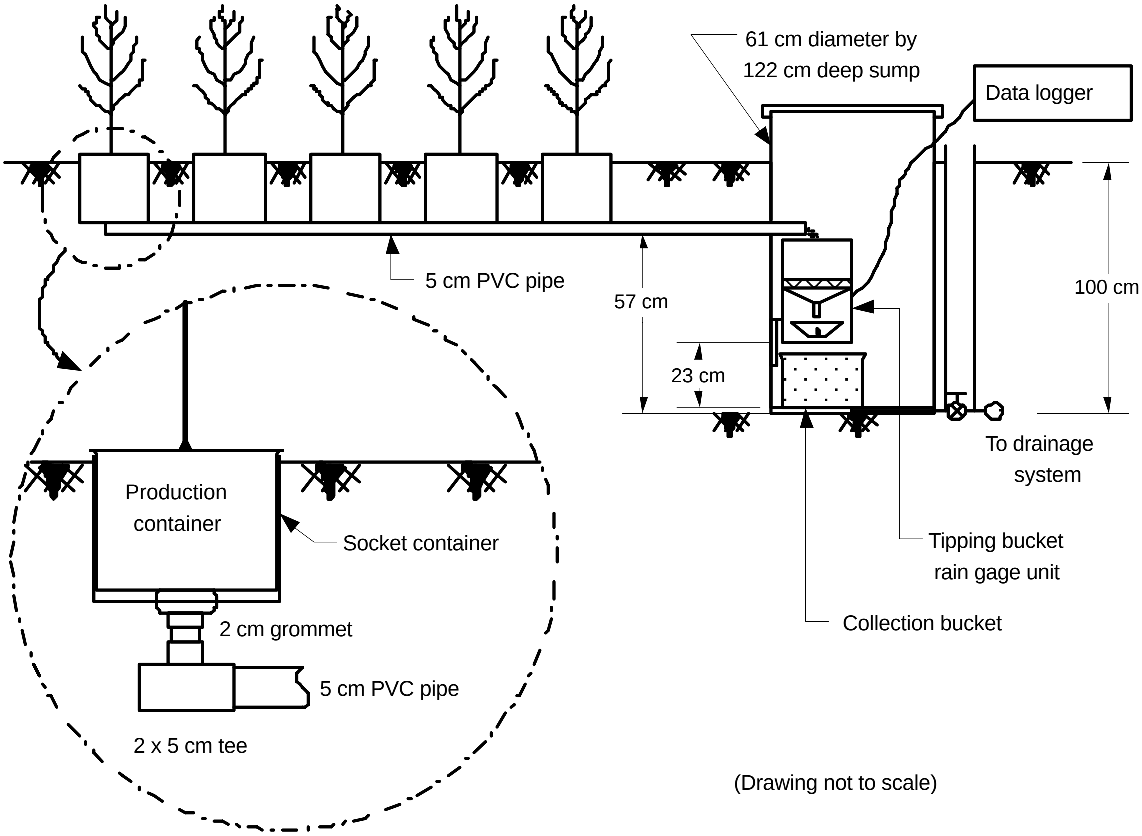

Figure 2. Installation of a rain gauge unit to measure drainage water from five pot−in−pot tree containers in a bed.

two zones. Each zone had five beds, and each bed had five pot−in−pot containers with trees. Spacing between the beds was 1 m, and spacing between the trees was 1.5 m. Each tree container had a volume of 58 L, was 43.2 cm in diameter, and was placed inside a socket container (fig. 2). The socket container was installed in the ground to the lip of the container. The potting media was composed of 55% pine bark, 3% sand, 5% Haydite soil conditioner, 20% sterilized regrind potting soil, 12% peat, and 5% composted municipal sludge. Red Sunset maple (*Acer rubrum* 'Franksred') trees were selected for the test because of their popularity in nursery production. The average tree caliper at 18 cm above the ground was 1.4 cm when transplanted to the system on July 1, 2003.

Each tree container was irrigated with a spray stake (Netafim USA, Fresno, Cal.) inserted vertically near the container side wall to ensure that all applied water was spread out within the container. Each bed had an irrigation supply line with a 70 kPa pressure regulator (model 32811, SennigerIrrigation, Inc., Orlando, Fla.) to minimize variations in application rate. An electric 24 VAC solenoid valve (model 12024E−10, Weather−Matic, Dallas, Texas) was installed upstream from the regulator in the water supply of each irrigation line to control the irrigation schedule for each bed. A manual gate valve and a solenoid valve were installed in the main water supply line to each zone. An inline vortex flow meter (model 1200, Fluidyne, Longmont, Colo.) was used to measure total flow rate and total amount of water applied in both zones. Irrigation programming was controlled with micro−switch actuated valves from a central control room. The experimental field system was designed in such a manner that it could also be used to evaluate water and nutrition use efficiency, drainage, and chemical leachate in drainage water for the pot−in−pot container nursery production (Zhu et al., 2004).

Some of the irrigation water applied to the tree containers drained through holes in the bottom of the containers into the socket containers. Socket containers had a single hole in the bottom. A 5 cm diameter PVC pipe was installed 7 cm below the five socket containers in each bed and connected to a 61 cm diameter and 122 cm deep sump at one end of the bed. The PVC pipe was connected to a socket container with a grommet and a tee (fig. 2). Drainage water from socket containers moved by gravity flow through the PVC pipe and was discharged into a rain gauge unit mounted inside the sump. A custom−designed bracket was used to mount each rain gauge unit vertically on the sump wall. A manual shutoff valve was installed under the sump to control discharge of the leached water to a collection and recycling system. Sumps were normally covered with lids.

The drainage water measurement device consisted of an electronic tipping−bucket rain gauge unit (model 3665R, Spectrum Technologies, Plainfield, Ill.). The rain gauge unit consisted of a magnet−operated switch, a freeze−resistant and self−emptying tipping bucket, a 20 cm diameter and 20 cm high rain collector, and a mounting bracket. The rain collector contained an inner funnel with a 6.35 mm diameter outlet to guide water to the tipping bucket. A #24 mesh screen was placed on the top of the inner funnel to prevent large particles from falling into the tipping bucket. A total of 10 rain gauge units were used for 50 container−grown trees in 10 beds.

Pulse signals produced from the magnet switches on the rain gauges were delivered to a micro data logger (model CR23, Campbell Scientific, Inc., Logan, Utah) for real−time measurement of the water flow. The data logger was connected with two synchronous communication modules (model AM25T, Campbell Scientific, Inc.) to allow multi−signal inputs simultaneously. The system acquired drainage water flow data once a minute. The total irrigation flow rate was collected each second only during the irrigation period.

The accuracy of the drainage flow measurement system was verified with two different size spray stakes during five separate weeks. At 70 kPa pressure, one spray stake (part 01SSAYL−36, Netafim USA, Fresno, Cal.) produced a flow rate of 11.6 L/h, and the other stake (part 01SSABK−36, Netafim USA, Fresno, Cal.) produced 27.1 L/h. Irrigation was applied two times a day, once in the morning and once in the afternoon. The 11.6 L/h spray stake was used in weeks 1, 2, 3, and 5. Total irrigation time was 6 min per day in week 1, 8 min per day in week 2, and 16 min per day in week 3. In week 5, irrigation was applied for 12 min on the first day, but was stopped when the plot received a total of 74.4 mm rainfall for the rest of the week. The 27.1 L/h spray stake was used in week 4 for 6 min per day.

To verify the accuracy of the rain gauge units, a 12 L collection bucket was placed under each rain gauge unit to measure the weekly amount of drainage water during August and September 2003. Since each sump was covered with a lid and the collection bucket was placed at the bottom of the sump, evaporation of the leached water was minimized. Water samples were taken from collection buckets three times during the growing season to determine drainage water density. Density of tap water used for calibration was also measured.

A portable weather station was installed 30 m away from the experimental system. Rainfall, ambient temperature, wind speed and direction, and solar radiation were recorded at 15 min intervals (Brazee et al., 2004).

Rain gauge units were calibrated prior to installation in the experimental system. The amount of water necessary to tip the bucket was determined by manually, slowly pouring tap water from a 10 mL graduated cylinder through the inner funnel to the tipping bucket until the bucket was tipped. Water in the cylinder was weighed before and after the test.

Calibrations of the rain gauge units were also conducted at various flow rates with the total volume of water ranging from 100 mL to 2000 mL (table 1). Tap water was stored in a 2 L plastic bottle. The bottle was suspended cap side down on a bottle holder. The cap was 0.5 cm above the top of the rain collector and faced downward toward the center of the inner funnel. Two equal−sized holes were drilled in the bottle, one in the bottom and the other in the cap. The hole sizes are listed in table 1. All calibrations were repeated three times with two out of ten randomly selected rain gauge units.

In calibration 1, a 1.02 mm diameter hole was used to determine tipping bucket counts for total water flows ranging from 100 mL to 2000 mL. Water slowly trickled into the rain gauge unit to simulate the situation at very low drainage flow rates in the pot−in−pot nursery production.

Table 1. Calibrations of the tipping−bucket rain gauge units.

Calibration	Hole Size (mm)	Volume of Water (mL)
1	1.02	100, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000
2	1.02, 1.40, 1.93	100, 200, 500, 1000, 2000
3	2.53, 3.18, 3.97, 5.55, 21.59	2000

In calibration 2, two hole sizes (1.40 and 1.93 mm) were used to investigate if the rain gauge units provide a linear relationship between amount of water and number of tips for different flow rates over a range of 100 mL to 2000 mL of water. A t−test with the paired experiments was used to analyze differences between the two rain gauge unit calibrations. All significant differences were determined at 0.05 level of significance.

In calibration 3, five hole sizes (2.53, 3.18, 3.97, 5.55, and 21.59 mm) were used to determine the influence of high flow rates on the number of tips. Only 2000 mL of water was used for this test. With the 21.59 mm diameter hole, water in the rain collector was sustained after the bottle emptied because the water flow to the rain collector was faster than from the inner funnel to the tipping bucket.

A micro data logger (model CR23X, Campbell Scientific, Inc.) was used to count the number of tips from the tipping switch closure of the rain gauge units for all calibrations. The number of tips was acquired and stored in the data logger every minute. This same acquisition frequency was used later in the field tests. Data was acquired from rain gauge units once a minute during the growing season after the system was established at the end of July 2003.

RESULTS AND DISCUSSION

The tipping bucket produced one tip per 7.59 mL when water was manually poured slowly into the rain gauge units. This is consistent with the manufacturer's claim that the unit could detect rainfall down to 0.25 mm in a single tip (0.25 mm over the opening area of 314 cm^2 = 7.85 mL). There were no significant differences in calibrations between two randomly selected rain gauge units with the amount of water ranging from 100 to 2000 mL.

Figure 3 shows results from calibration 2 for the calibration curves between the volume of water discharged into the tipping bucket and the number of tips produced with three different size holes. For each individual hole size, there was a linear relationship between the amount of water and the number of tips. However, the slope of the calibration curves varied with the hole size. That is, the number of tips decreased as the flow rate to the tipping bucket increased (table 2).

Results from calibration 3 indicated that the volume per tip from the tipping bucket increased nonlinearly as the tipping frequency increased (fig. 4). The relationship between the volume per tip and tipping frequency corresponds to a polynomial regression equation:

$$Y = 7.456 + 0.135X - 0.00086X^2 \tag{1}$$

with r^2 = 0.995, where Y is the volume per tip (mL/tip), and X is the tipping frequency (tips/min). Since the number of tips from the rain gauge unit was recorded every minute in the field system, the volume of drainage water detected by a rain gauge unit within a minute should be the product of number of tips and the volume per tip. Therefore, the amount of drainage water (V) in mL passing through a tipping bucket within a minute would be:

$$V = X \cdot Y = X\left(7.456 + 0.135X - 0.00086X^2\right) \tag{2}$$

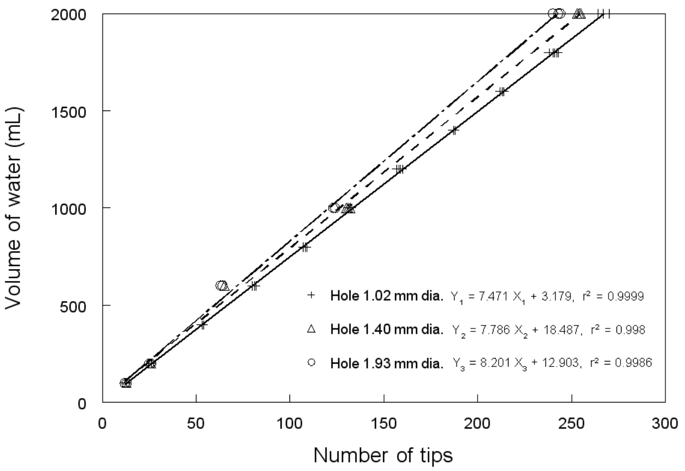

Figure 3. Calibration of tipping−bucket rain gauges with amounts of water ranging from 100 to 2000 mL discharged from three different size holes.

The daily total amount of drainage water through a rain gauge unit was the summation of the volume of drainage water from each of the 1440 minutes in a 24 h period.

Very few sediments and particles were found in drainage water samples, although the color of the water samples appeared brownish. The average density of the water samples collected from the drainage water at three different times was 992.0 g/L, while the density of the tap water used for calibration was 991.9 g/L.

Table 3 shows the comparison for amounts of drainage water collected in the 12 L collection buckets and that measured by the rain gauge units in the 10 sumps. Except for week 5, the amounts of water measured with the rain gauge units were very close to that collected with the collection buckets. The maximum difference in the amount of drainage water between two methods was 0.098 L from sump 3 in the week 1, 0.277 L from sump 8 in week 2, 1.215 L (or 5.3% error) from sump 2 in week 3, and 0.522 L from sump 10 in week 4. In week 5, because a high amount of rainfall was received during one evening, the collection buckets overflowed, and some water puddled around the outside of the socket containers and entered the socket containers without first going through the tree containers. The problem was solved by lowering soil surface outside the socket containers after the event occurred. During weeks 1 and 2, the weekly drainage was considerably lower due to the low irrigation rate. When irrigation time was increased from 8 min (week 2) to 16 min (week 3), the average weekly drainage volume for the 10 beds increased from 0.282 L to 9.371 L, an increase of 33 times. Similarly, when the irrigation rate was increased from 11.6 L/min (week 1) to 27.1 L/min (week 4) with 6 min daily application, the weekly amount of drainage water increased from 0.390 L to 4.750 L. Therefore, to avoid excessive drainage water loss, irrigation schedule and application rate should be carefully managed.

The system containing the rain gauge units was able to provide real−time measurement for the volume of drainage water after irrigation. Figures 5a and 5b show the minute−by−minute volume of drainage water measured by the tipping−bucket rain gauges in sumps 1, 4, and 8 with daily average irrigation application rates of 7.7 L and 15.5 L, respectively, to each of five container−grown trees. The time when drainage started after irrigation varied with the irrigation application rate. The average start time from the 10 beds was 22.3 min after irrigation was started for the 7.7 L daily irrigation and 7.6 min for the 15.5 L daily irrigation. The initial peak drainage flow lasted less than 25 min for the 7.7 L irrigation and 40 min for the 15.5 L irrigation. After the peak flow period, drainage decreased to a trickle.

In pot−in−pot nursery production systems, drainage cannot be visualized directly because it occurs at the bottom of in−ground containers. Therefore, the tipping bucket system can assist in determining the amount of irrigation required for the pot−in−pot nursery production before

Table 2. Average flow rate to the tipping bucket and number of tips produced from the rain gauge unit after 2000 mL of water was discharged with various sizes of holes in the calibration bottle.

Hole Diameter (mm)	Average Flow Rate (mL/min)	Number of Tips[a]
1.02	24.05	267 ±3
1.40	58.25	254 ±1
1.93	100.00	242 ±2
2.53	250.00	197 ±2
3.18	325.58	191 ±1
3.97	666.67	169.5 ±0.5
5.55	886.08	163.5 ±1.5
21.59	992.91	160 ±1

[a] From two randomly selected rain gauge units with three replications.

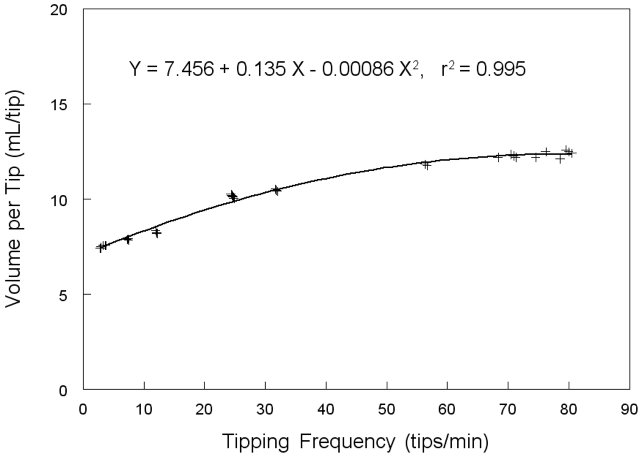

Figure 4. Relationship between volume per tip and tipping frequency for the tipping−bucket rain gauge.

Table 3. Weekly total volume of drainage water (L) due to different irrigation application rates and rainfall directly measured with 12 L collection buckets and indirectly measured with rain gauge units during the five week tests.

	Week 1		Week 2		Week 3		Week 4		Week 5[a]	
Sump	CB[b]	Tip[c]	CB	Tip	CB	Tip	CB	Tip	CB	Tip
1	0.001	0.068	0.000	0.053	12.730	12.435	6.750	6.581	14.590	27.908
2	0.001	0.023	0.000	0.023	22.930	21.715	3.960	4.153	13.410	33.615
3	0.710	0.808	0.000	0.030	4.550	4.375	4.900	4.800	13.320	20.753
4	0.002	0.038	0.000	0.000	7.150	7.493	4.450	4.775	14.350	17.543
5	0.000	0.015	0.000	0.000	0.920	1.020	3.600	3.480	11.420	19.980
6	0.640	0.593	0.200	0.030	16.700	15.660	4.400	4.845	16.410	27.368
7	0.010	0.060	0.000	0.015	5.300	5.220	1.800	1.924	15.430	30.000
8	n/a	1.745	2.010	1.733	4.230	3.930	6.200	6.770	14.640	35.228
9	0.002	0.053	0.000	0.030	9.480	9.240	2.660	2.370	16.940	29.093
10	0.441	0.495	0.700	0.908	12.330	12.618	8.320	7.798	16.310	38.303
Mean	0.201	0.390	0.291	0.282	9.632	9.371	4.704	4.750	14.682	27.979

[a] During week 5, the plot received 74.4 mm of rainfall, and collection buckets overflowed.
[b] CB = 12 L collection bucket.
[c] Tip = tipping−bucket rain gauge.

drainage starts. With this information, irrigation application might be optimally managed with minimum water loss due to drainage.

The cumulative amount of drainage water was calculated from the real−time measurement of water flow during each minute. Figures 6a and 6b show the cumulative amounts of drainage measured by the tipping−bucket rain gauges at sumps 1, 4, and 8 with daily irrigation application rates of 7.7 L and 15.5 L, respectively, to each of five container−grown trees. The cumulative amount of drainage increased as the daily irrigation rate increased. For example, the daily cumulative amount of drainage from the five containers connected to sump 1 was 1.108 L and 8.880 L when the daily irrigation was 7.7 L and 15.5 L, respectively, to each of five container−grown trees. The amount of drainage during the initial peak period due to irrigation was a large portion of the total accumulated drainage. Figure 6 also illustrates that the cumulative drainage varied considerably between the sumps. Such differences might be caused by the variations in soil porosity, tree sizes in the different containers, and other unknown factors.

The system was also able to measure the amount of drainage due to precipitation received by the tree containers. Figure 7 shows the cumulative drainage from 5 of 10 beds within 40 h due to 33.3 mm of rainfall that reached the containers during 16 h. The five container−grown trees in each bed received 6.5 L of irrigation about 4 h before the rain started. Among the 10 beds, bed 1 drained the most water, while bed 3 drained the least water within 40 h. A large portion of the rainfall collected in the tree containers was lost through drainage when rainfall was heavy and intense. During the 40 h period after 33.3 mm of rainfall, the total amount of drainage was 21.9, 11.72, 12.19, 19.52, and 18.77 L through beds 1, 3, 5, 7, and 9, respectively. This heavy rainfall produced much more drainage than the normal irrigation application. In irrigation management, water loss through drainage after irrigation or intensive rainfall should be considered to avoid damaging trees from lack of water.

CONCLUSIONS

The system was able to provide real−time measurement of drainage due to irrigation and rainfall for pot−in−pot nursery production, and can provide an experimental means to gain knowledge on irrigation management techniques to improve

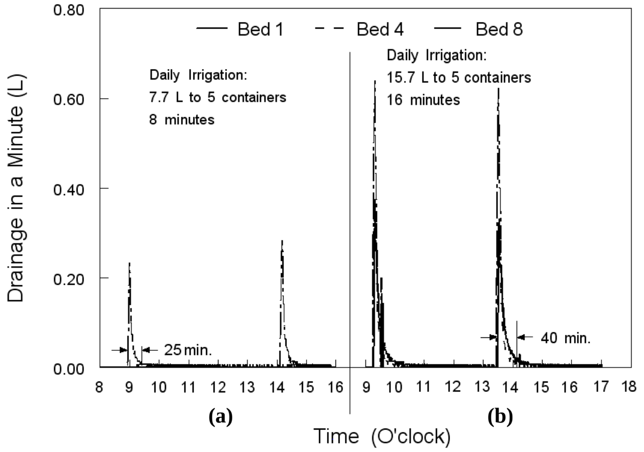

Figure 5. Real−time measurement of drainage water by tipping−bucket rain gauges for five container−grown trees in each bed with two different irrigation application rates and two times a day: (a) 7.7 L daily irrigation, and (b) 15.5 L daily irrigation.

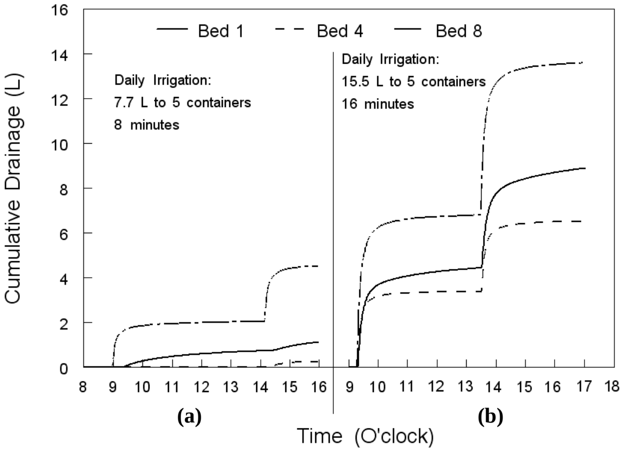

Figure 6. Cumulative amounts of drainage water measured by tipping−bucket rain gauges for five container−grown trees in each bed with two different irrigation application rates and two times a day: (a) 7.7 L daily irrigation, and (b) 15.5 L daily irrigation.

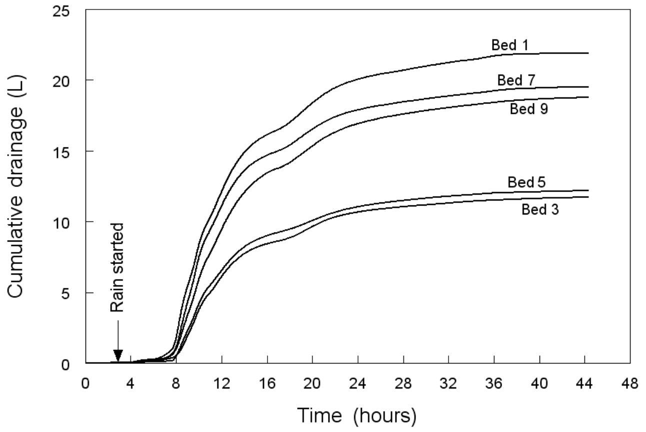

Figure 7. Cumulative amount of drainage water measured by tipping−bucket rain gauges for five container−grown trees in each bed when total rainfall (33.3 mm) reached the pot−in−pot nursery plot.

irrigation water use efficiency and reduce water and nutrition losses.

The nonlinear equation developed to calculate the volume of drainage water from the number of bucket tips per minute agreed well with the experimental data from the 12 L collection buckets for various irrigation application rates. The volume of drainage in a minute was the product of the number of bucket tips and the volume per tip.

ACKNOWLEDGEMENTS

The authors thank K. A. Williams, A. A. Doklovic, D. T. Troyer, B. E. Nudd, and Hong Tang for conducting tests and technical assistance. The authors also gratefully acknowledge T. Demaline, President, and D. Hammersmith, Nursery Manager, Willoway Nurseries, Inc., Avon, Ohio, for their cooperation in providing operating facilities and experimental field space.

REFERENCES

Barfield, B. J., and M. C. Hirschi. 1986. Tipping bucket flow measurements on erosion plots. *Trans. ASAE* 29(6): 1600−1604.

Beeson, R. C., Jr., and E. F. Gilman. 1995. Irrigation and fertilizer placement affect root and canopy growth of trees produced in in−ground fabric containers. *J. Environ. Horticulture* 13(3): 133−136.

Beeson, R. C., Jr., and K. Keller. 2003. Effect of cyclic irrigation on growth of magnolias produced using five in−ground systems. *J. Environ. Horticulture* 21(3): 148−152.

Bentz, W. W., and C. R. Amerman. 1968. A tipping bucket device for measuring very low flows. *Agric. Eng.* 49(12): 750−751.

Brakensiek, D. L., H. B. Osborn, and W. R. Rawls (coordinators/editors). 1979. *Field Manual for Research in Agricultural Hydrology*, 75−214. Agricultural Handbook 224. Washington, D.C.: USDA, U.S. Government Printing Office.

Brazee, R. D., K. A. Williams, D. Lohnes, R. C. Derksen, H. Zhu, R. Zondag, and C. R. Krause. 2004. The USDA Agricultural Research Service Research Weather Station Network in Northern Ohio Nurseries. In *Ornamental Plants Annual Reports and Research Reviews, 2003*, 190−193. Special Circular 193. Wooster, Ohio: The Ohio State University, Ohio Agricultural Research and Development Center.

Edwards, I. J., W. D. Jackon, and P. M. Fleming. 1974. Tipping bucket gauges for measuring runoff from experimental plots. *Agric. Meteorology* 13(2): 189−201.

Hanna, E. 1995. How effective are tipping−bucket rain gauges? A review. *Weather* 50(10): 336−342.

Johnson, C. W., H. D. Copp, and E. R. Tinney. 1966. Drop−box weir for sediment−laden flow measurements. In *Proc. American Society of Civil Engineers* 92(HY5): 165−190.

Johnston, C. N. 1942. Tilt buckets for measuring run−off and erosion. *Agric. Eng.* 23(5): 161−162.

Khan, A. A. H., and C. K. Ong. 1997. Design and calibration of tipping bucket system for field runoff and sediment quantification. *J. Soil and Water Conservation*52(6): 437−443.

Lenz, A. T. 1943. Viscosity and surface tension effects on V−notch weir coefficients. *Trans. American Society Civil Engineers* 108: 759−802.

Meyer, L. D., and D. L. McCune. 1958. Rainfall simulator for runoff plots. *Agric. Eng.* 39(10): 644−648.

Ruter, J. M. 1997. The practicality of pot−in−pot. *American Nurseryman* 185(1): 32−37.

Yu, B., C. A. A. Ciesiolka, C. W. Rose, and K. J. Coughlan. 1997. A note on sampling errors in the rainfall and runoff data collected using tipping bucket technology. *Trans. ASAE* 40(5): 1305−1309.

Zhao, S. L., E. C. Dorsey, S. C. Gupta, J. F. Moncrief, and D. R. Huggins. 2001. Automated water sampling and flow measuring devices for runoff and subsurface drainage. *J. Soil and Water Conservation* 56(4): 299−306.

Zhu, H., C. R. Krause, R. C. Derksen, R. H. Zondag, R. D. Brazee, N. R. Fausey, 2004. New techniques for monitoring drip irrigation water use efficiency, drainage, and leachate in container nurseries. ASAE Paper No. 042247. St. Joseph, Mich.: ASAE.