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Verification of Turfgrass Evapotranspiration in Utah

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VERIFICATION OF TURFGRASS EVAPOTRANSPIRATION

IN UTAH

Final Report

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EXECUTIVE SUMMARY

Verification of turfgrass consumptive use was accomplished with field studies generally during 2002-2008 in four areas of Utah: Cache Valley (Logan Golf and Country Club), Salt Lake County (Murray Parkway Golf Course), Utah County (Brigham Young University [BYU] Spanish Fork Farm 2002-06) and Washington County (Sunbrook Golf Course, 2002-06 and Southgate Golf Course, 2004-08). Two lysimeters were installed at each of the three sites outside Cache Valley in late 2001 and early 2002. The existing two lysimeters in Logan continued to be used. In April 2004 a third lysimeter was installed at Logan and two lysimeters were installed at Southgate Golf Course in St. George. Irrigation and rain as well as drainage were measured at each lysimeter at intervals during the growing season. Water use of the turfgrass was set equal to the difference between measured irrigation and rain fall and the amount of drainage water.

Weather data for use with a Penman combination type ET equation was collected with electronic weather stations (Campbell Scientific, Inc.) at each site. Crop coefficients were calculated as the ratio of turfgrass water use to alfalfa reference evapotranspiration (ET_r) calculated with the ASCE Standardized Penman-Monteith ET equation (denoted as ET_{rs}).

Observed seasonal turfgrass consumptive use varied from 11.2 inches (Logan West, 2004,) to 50.0 inches (Southgate, 2007). The range at Logan was 11.2 (West, 2004) to 35.2 inches (new, 2007); at Murray, 22.2 (East 2008) to 30.5 inches (East 2005); at Southgate, 19.7 (East 2006) to 50.0 inches (West 2007); at Spanish Fork), 14.2 (South 2002) to 30.4 inches (North 2004) and 13.0 (East 2004) to 35.5 inches (West 2002) at Sunbrook. Direct comparison of such variation in ET values across years and sites is problematic due to differing growing season lengths from year to year, site environmental conditions (average temperatures and wind patterns), and elevation (range of 2600 to 4800 ft above msl) from south to north in Utah (latitude range of 37° N to 42° N).

The multi-year average seasonal observed (based only on individual lysimeter ET) crop coefficient values varied from 0.34 (Logan West) to 0.65 (Southgate West). Study period average seasonal K_c values by lysimeter were: Logan 0.59 (new), 0.42 (east), 0.34 (west) and site average of 0.45; Murray 0.57 (both east and west) and site average of 0.57; Southgate 0.53 (east), 0.65 (west) and site average of 0.59; Spanish Fork 0.58 (north), 0.54 (south) and site average of 0.56 and Sunbrook 0.49 (east), 0.46 (west) and site average of 0.47. Average two lysimeter seasonal K_c values at Murray and Spanish Fork were similar (0.57 and 0.56, respectively) although there was less across year variation at Spanish Fork.

An alfalfa reference (ET_r) based seasonal average crop coefficient, K_{cr}, value of about 0.60 reasonably represents a well watered turfgrass, cutting height of 1.5 to 2 inches, in the central and northern parts of the state, whereas a K_{cr} of 0.65 would similarly be reasonable to use in the lower elevation and warmer southern Utah's Dixie. These K_{cr} values, 0.60 and 0.65, are, respectively, about 7% and 16% higher than the K_{cr} of 0.56 used in earlier estimates of turfgrass evapotranspiration across Utah (Hill, 1994).

Monthly K_{cr}, and subsequently grass reference based K_{co}, values were derived for four of the lysimeters: Logan – new, Spanish Fork – north, and both Southgate lysimeters by prorating observed lysimeter ET between adjacent months using the number of days in the measurement interval. Further data adjustments were made upon final analysis by discarding obvious outliers from the average monthly K_c values.

The monthly crop coefficient, K_{cr}, for the higher elevation northern majority of Utah begins with a value of 0.45 starting at turf green up and remains at 0.45 for about 20 days until the turf begins active growth. The K_{cr} value then increases linearly over about 30 days to a value of 0.60 when the turf reaches full and growth. The turf K_{cr} remains at 0.60 for the duration of the season until cool fall temperatures result in reduced turf growth rates. This is typically around mid-October, after which K_{cr} decreases linearly toward 0.45 in early November and remains at that value until dormancy.

The monthly K_{cr} curve for lower elevation southern Utah is similar; however, it continues for the full year beginning in January at a value of 0.50 during the semi-dormant period. In late February to early March the K_{cr} value begins to increase linearly over a 30 day period to a value of 0.65, and remains at 0.65 for the majority of the season until the growth slows in mid to late October. The K_{cr} value then decreases linearly to a value of 0.50, typically reached in mid November and remains at 0.50 until the following spring. In both sets of suggested crop coefficient curves, maintaining the mid-season K_{cr} at a constant value, 0.60 or 0.65, ignores the indication of a “summer slump” in turf water use.

Grass reference based crop coefficient, K_{co}, values were derived from K_{cr} by multiplying K_{cr} by about 1.2. Thus, mid-season K_{co} values of 0.70 for northern Utah and higher elevations and 0.80 for southern Utah and lower elevations were obtained by rounding to the nearest 0.05. Corresponding early and late season K_{co} values are 0.50 and 0.60, respectively, for northern higher elevation and southern lower elevation Utah.

ACKNOWLEDGEMENTS

The work described herein was performed under a contract between the Utah Department of Natural Resources, Division of Water Resources and Utah State University (Department of Biological and Irrigation Engineering[BIE]). This contract was initiated in July 2001 to perform field research using lysimeters at selected Utah locations to verify previously used consumptive use (evapotranspiration) factors for turfgrass. The contract was originally expected to end June 30, 2005. However, the termination was extended through June 30, 2008 to allow collection of three additional full years of data (2005-2007) on the new (April 2004) lysimeters at Logan and Southgate. Subsequently, an additional year (2008) of data was collected at Logan, Murray and Southgate and is included herein.

Gratitude is expressed to the following individuals who collected field data from 2002 – 2008: David Carruth, Murray Parkway Golf Course superintendent; Earl Hansen, BYU Agronomy Dept; Rick Heflebower, Washington County Extension agent; Julie Breckenridge, Washington County Water Conservancy District; Sergio Solis, Sunbrook Golf Course superintendent; Conrad Barrow, Sunbrook Golf Course; Sherrie Fox, Southgate Golf Course and USU BIE stuents Burdette Barker, Musa Dlamini, Darren Fillmore, Wesley Hopwood and Ryan McBride. Musa, Ryan, Darren, Michael Kohler and Omar Alminagorta provided valuable analysis of seasonal lysimeter and weather data for annual reports. Burdette provided considerable assistance with the final report. The assistance of Nancy Hanks, Allison Barnes, Kelly McKee, Megan Poulton, and Shelley Comendant, USU BIE staff assistants is appreciated for their help in preparing the various annual reports. Particular gratitude is extended to Rebeca Olsen for her word processing and editing skills in completing the final report.

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INTRODUCTION

The continued competition for water in Utah necessitates accurate estimates of water needs and management requirements for legal water allocation as well as hydrologic considerations. Competition for water is due to increased urban and rural development as well as declining ground water levels and recurring drought conditions. This highlights the importance of careful water management including urban water conservation, particularly along the Wasatch front and in high growth areas of Utah. The majority of urban water use in the summer is from irrigation of landscaped areas, mostly turf. Thus, it is important to accurately estimate turfgrass water use to support water conservation efforts.

Previous statewide estimates of irrigated crop water use (evapotranspiration, or ET) in Utah relied on a combination of near state- of-the-art methodology (Penman type ET equation, 1982 Kimberly, ID version) at the time coupled with a calibrated Blaney-Criddle equation (Hill, 1994). A crop coefficient value for turfgrass ET of 0.56 was used with the 1982 Kimberly Modified Penman Combination alfalfa reference ET equation. This coefficient value was based on two years of data, as of 1993, from lysimeters installed in the Logan Golf and Country Club golf course. Ervin and Koski (1998), reporting a Colorado study, suggested that water could be conserved by irrigating turf every three days with a K_c of 0.7 (reference alfalfa, ET_r, basis) for Kentucky bluegrass and 0.6 for turf type tall fescue. These coefficient values for fescue and bluegrass were about 7 to 25 % higher, respectively, than the Report # 145 value. This, plus other concerns, suggested that the coefficients derived from the Logan Golf and Country Club site in Cache Valley may not be applicable throughout Utah. Thus, site specific verification in a range of conditions was indicated to increase confidence in turfgrass water use estimates.

The originally anticipated product of this research was to determine verified crop coefficients, K_c, (Wright, 1982) for use with the 1982 Kimberly Penman ET_r equation (Jensen, Burman and Allen, 1990) along with daily weather data to estimate near real time turfgrass water use in urban areas of Utah. However, subsequent to the initiation of this work, the American Society of Civil Engineers (ASCE) and the Irrigation Association adopted a “standardized” form of the Penman-Monteith ET_r equation (Allen, et al., 2005). The desire among Utah’s state water agencies to use the “standardized” method provided an opportunity to calibrate it for use in estimating turfgrass consumptive use throughout Utah.

Objectives

The primary purpose of this work was to verify turfgrass crop water use coefficients for use with either a grass reference ET (ET_0) or an alfalfa reference (ET_r) equation value. Specifically, the two main objectives were:

A. Study turfgrass water use by measurement with lysimeters including collection of sufficient weather data at each site for use with a Penman type combination reference ET equation.

B. Analysis of previously collected turfgrass irrigation and soil water content data at the BYU Agronomy Farm near Spanish Fork, Utah. Neutron probe and other data were collected during 1990 - 1992 (or 1993, approximately) from the BYU turf plots. However, usable <u>concurrent</u> weather data, soil water measurements, and irrigation data were not obtained for any time period for these studies. Thus, this portion of the study, as included in the original proposal, was abandoned.

Work tasks by objective, as contained in the proposal, are given in Appendix A.

Evapotranspiration Estimation

Evapotranspiration is a relatively complex and nonlinear phenomenon, depending on the interaction of air temperature, solar radiation, wind, vapor pressure (relative humidity), as well as on the crop type and growth stage (leaf area). Evapotranspiration (ET), consumptive use, or crop water use can be estimated or measured by many different techniques depending on study objectives and financial and data resources. These techniques range from equations that use only monthly average temperatures to thoroughly instrumented field research sites with weighing lysimeters. Additional data on crop water use are available from irrigation scheduling, experimental plots, and field research studies.

The general form of the reference ET - crop coefficient approach to consumptive use equations is:

$$ET = K_c\ ET_r + E_{ws} \quad (1)$$

where ET is the estimated crop evapotranspiration; K_c is an empirically determined crop coefficient relating crop ET to reference crop ET_r; ET_r is calculated ET for an alfalfa reference crop; and E_{ws} is estimated wet soil surface evaporation adjustment to account for conditions occurring following an irrigation or significant rain. This adjustment is made when the K_c value is less than 1.0, e.g., in the early growth stages of a row crop or following a cutting of alfalfa. E_{ws} should be ignored in situations where the K_c factor includes the effect of a wet soil surface on E. However, the irrigation schedule should approximate that of the site where the K_c values were determined. Implied in Eq. 1 is a K_c value representing the "basal" condition (K_{cb}) since E_{ws} is explicitly shown.

An alternate form of the crop water use equation is:

$$ET= K_{cm}\ ET_r \quad (2)$$

where K_{cm} is a "mean" crop coefficient (Wright, 1982) that includes the effect of evaporation from a wet soil surface from a typical irrigation schedule for the given crop.
The value of a crop coefficient (K_c or K_{cm}) at a particular growth stage depends on plant transpiration as well as evaporation from the soil surface. Care must be exercised in applying K_{cm} values from one research site to other sites with different irrigation practices and conditions.

A reference crop of alfalfa is at least 14 inches (35 cm) tall and adequately irrigated so that transpiration is not limited by available soil moisture. Another common reference is that of clipped grass (ET_0), water not limiting. The availability of reasonably priced electronic weather stations has allowed routine use of Penman type equations for estimating reference crop ET (ET_r).

Reference Crop Evapotranspiration

The ASCE Standardized Reference Evapotranspiration Equation was used in order to obtain well accepted reference evapotranspiration (ET_{rs}) values. Due to nighttime high wind conditions at the Logan Golf and Country Club, it was decided that daily sums of hourly calculated ET_{rs} should be used. This was because the high wind at night when temperatures are cool, and turfgrass stomata are closed, results in a high calculation of ET_r if calculations are made using 24 hour data only. A program was written in Visual Basic for calculating daily ASCE standardized ET_{rs} by summing hourly ET_r values.

Many reference evapotranspiration equations have been used historically. As mentioned previously, the American Society of Civil Engineers (ASCE) and the Irrigation Association adopted a "standardized" form of the Penman-Monteith ET_r equation in 2005 (Allen, et al., 2005). This equation is now a generally accepted method of calculating ET_r. The ASCE standardized Penman-Monteith equation overestimates ET_r in the spring and fall at Kimberly, Idaho (Wright et al., 2000), where the 1982 Kimberly modified Penman combination equation was calibrated, thus necessitating the use of "corrected" crop coefficients (Allen and Wright, 2002).

The ASCE Standardized Penman-Monteith ET_{rs} equation can be used for both a "tall" (alfalfa) or "short" (grass) reference crop calculation mode:

$$ET_{rs} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{C_n}{T + 273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + C_d u_2\right)} \quad (3)$$

where ET_{rs} is the standardized reference evapotranspiration (mm/d or mm/hr) for a "tall" crop (denoted by the subscript "rs"), Δ is the slope of the saturation vapor pressure – temperature curve (kPa/°C), R_n is the calculated net radiation at the crop surface (MJ/ m^2/d or MJ/ m^2/hr), G is soil heat flux (MJ/ m^2/d or MJ/ m^2/hr), γ is the psychrometric constant (kPa/°C), C_n is the numerator constant (changes with time step and reference crop type) (K mm s^3/Mg/d or K mm s^3/Mg/hr), T is mean temperature for the calculation interval (daily or hourly) (°C), u_2 is mean wind speed for the calculation interval at a height of 2 m above the ground (m/s), e_s is the saturation vapor pressure at 2 m above the ground (kPa), e_a is the mean actual vapor pressure at 2 m above the ground (kPa), C_d is the denominator constant (changes with time step and reference type (s/m).

The units for the coefficient 0.408 are m^2 mm/MJ. For this study a "tall" crop (alfalfa) was used as the reference type and the calculations were performed on an hourly basis.

W

Water Balance Estimates of Evapotranspiration

When applied to an irrigated plot, the mass balance equation can be represented as:

$$P + I + R_i + Up = ET + DP + R_o + \Delta S \qquad (4)$$

where P is precipitation, I is irrigation, R_i is surface flow onto the field, Up is capillarity or upward flow, DP is deep percolation, R_o is runoff and ΔS is change in soil moisture ($SW_1 - SW_2$). The use of lysimeters eliminates the turfgrass R_i, Up, and R_o terms in Eq. 4. Thus, since P, I, DP and ΔS can be measured, the ET term can be estimated as the residual.

PROCEDURES

Lysimeter Techniques for Measuring Turfgrass Water Use

A lysimeter is a tank filled with soil that contains the same vegetation as the adjacent area. A lysimeter isolates the soil mass and vegetation so water cannot enter or leave, thus making it possible to accurately monitor water required to maintain plant growth to determine evapotranspiration (ET) or consumptive use. ET is often determined with lysimeters that weigh changes in the soil moisture. The scope of this study and cost of weighing lysimeters made non-weighing, drainage type lysimeters a reasonable alternative. This type of non-weighing lysimeter was used in a field estimation of wet meadow ET in the Upper Bear River of Idaho, Utah and Wyoming (Hill, et al., 1989); in a study of hydrophyte (bulrush and cattail) water use in Cache Valley, Utah (Allen, Prueger and Hill, 1992) and in a study of ET from formerly irrigated lands in the South Park area of Colorado (Quinlan, Burman and Siemer, 1982). Two lysimeters were previously (fall of 1991) installed in the Logan Golf and Country Club and continued in use through this study.

Lysimeters specifically for this study were fabricated in early fall 2001 and installed, two at each site, beginning in November 2001 at St. George (Sunbrook Golf Course) and Murray Parkway Golf Course and in spring 2002 at the BYU Spanish Fork Farm. Subsequently, two more lysimeters were installed at Southgate Golf Course (2004, St. George) and one more at Logan making three at Logan and eleven total at the five sites.

Construction

The lysimeters were constructed from 10 gauge steel plates, which were cut and bent. The joints were arc-welded and the lysimeters were then powder coated (white). The lysimeters are 11.1 square feet (40 inches x 40 inches) and 18, 24, or 30 inches deep, depending on site and fabrication date, with a drainage pipe outlet in a corner. A perforated 3 or 4 inch diameter plastic drainage pipe was placed diagonally across the bottom. Typical installation plan and cross-section views of installed lysimeters are shown in Figure 1.

Installation Methods

Lysimeters were installed in representative areas of irrigated turf. The sod mat was removed with a shovel and remaining material was removed and placed on sheets of plywood in the order of removal (Fig. 2). A lysimeter was placed in the excavated hole and leveled. A lip of approximately ½ to 2 inches protruded above the ground to prevent surface water from entering the lysimeter. The plastic drainage pipe was placed in the lysimeter as shown in Figure 3. The drainage pipe was covered by about 2 inches of sand and the soil removed in excavating the hole was replaced in 8 to 10 inch lifts and compacted. Intact sod pieces removed during excavation were replaced (Fig 4) in similar pattern as in a jig-saw puzzle. Similar installation was realized at each location and the vegetation in the lysimeters was representative of that in the surrounding area (Fig 5).

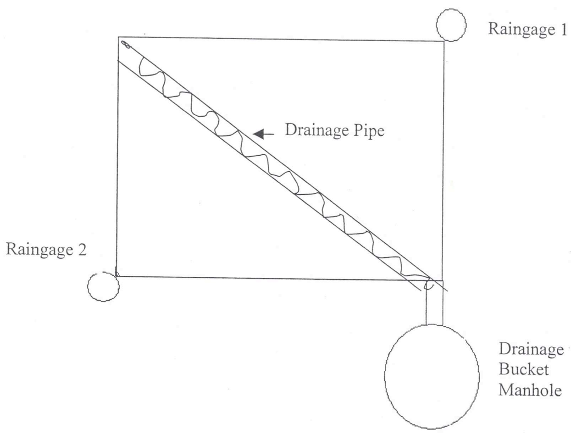

FIGURE 1A. PLAN VIEW OF INSTALLED LYSIMETER (TYPICAL). AFTER DLAMINI (2003)

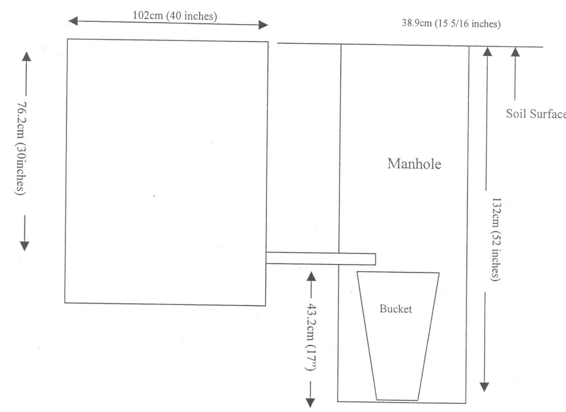

FIGURE 1B. CROSS-SECTION VIEW OF INSTALLED LYSIMETER (TYPICAL). AFTER DLAMINI (2003)

FIGURE 2. EXCAVATION OF LYSIMETER PLOT (SUNBROOK, NOV 2001)

FIGURE 3. PLASTIC PERFORATED DRAIN PIPE IN LYSIMETER BOTTOM AND CORNER RAIN GAGE WELL (SOUTHGATE, APR 2004)

FIGURE 4. PLACEMENT OF SOD IN PARTIALLY INSTALLED LYSIMETER (SOUTHGATE, APR 2004)

FIGURE 5. FINISHED LYSIMETER INSTALLATION (SOUTHGATE, DEC. 2004)

A 15-inch diameter PVC pipe was placed vertically in a hole adjacent to the drain pipe outlet. This was covered with a steel lid (Fig 4) and served as a manhole for the 5 gallon (at Logan) or 6 gallon drainage buckets. Four-inch diameter rain gages were placed in 6-inch diameter PVC pipes sunk into the ground outside two opposite corners of the lysimeters (Fig 3). The tops of the rain gages were approximately flush with the surface. Installation dates and lysimeter depth are given in Table 1.

The vegetation in the lysimeters was managed the same as the adjacent turf. When installation was in the spring, measurements began immediately, even though the turf may not have been fully established.

TABLE 1: INSTALLATION DATES AND DEPTH OF LYSIMETERS

Location		Lysimeter Installation Date	Depth (in)
Logan Golf and Country Club	East & West	September 17, 1990	18
	New	April 7, 2004	24
Murray Golf Course		November 16, 2001	30
South Gate Golf Course		April 8, 2004	24
Spanish Fork		April 9, 2002	30
Sunbrook Golf Course		November 15, 2001	30

FIELD PROCEDURES (DATA COLLECTION)

All lysimeter sites were visited weekly during the early and late growing season, usually mid-April and through October. Whereas twice weekly visits were made in the mid-growing season where drainage amounts could have caused overtopping of the buckets at longer observation intervals. Twice weekly visits were generally made at Logan, Spanish Fork and Southgate. At each visit measurements were made of water in the two rain gages and the volume or depth of water in the drainage bucket. If necessary, grass was clipped from around the rain gages. A protocol for the lysimeter observations is in Appendix B.

The drainage (if any) was measured with a 1000 ml graduated cylinder; larger drainage amounts were measured as two depth readings in the drainage bucket, taken at opposite sides of the bucket. After each reading rain gages and drainage buckets were emptied.

Occasionally additional water was added to some of the lysimeters in order to induce drainage. This was typically done on lysimeters which had not produced drainage for an extended period of time.

Consumptive use, evapotranspiration, of the lysimeter vegetation was calculated using a simple water balance equation:

$$CU = ET_{lys} = \Delta SW + (Irrigation + Rain) + W_{added} - Drain \tag{5}$$

where CU is consumptive use, equivalent to evapotranspiration, ET_{lys}; ΔSW is change in soil water; (Irrigation+ Rain) is the content of a rain gage (which could be both irrigation and/or rain); W_{added} is extra water added to the lysimeter (by dumping buckets of water as described above) and Drain is drainage water in the bucket. The change in soil water, ΔSW, was assumed to be negligible as long as drainage occurred regularly. However, during some seasons and particularly at Murray, drainage did not occur for several weeks at a time.

WEATHER DATA COLLECTION

Automated electronic weather stations (EWS) were equipped to monitor air temperature, soil temperature, relative humidity, solar radiation, wind speed, wind direction (except at Logan) and precipitation. The sensors were sampled every 10 seconds and hourly and daily maximums, minimums, averages, and totals were calculated and saved in on-board memory. Each station was outfitted with a Campbell Scientific, Inc. (CSI) CR10X micrologger (CR10 at Spanish Fork). The sensors and data logger were mounted on CSI tripod instrument platforms (Figure 6). Specific instrumentation component packages for each station are listed in Appendix C.

FIGURE 6. TYPICAL ELECTRONIC WEATHER STATION INSTALLATION (SOUTHGATE LOOKING NORTHWARD, 05103 ANEMOMETER)

Weather station locations (coordinates) are given in Table 2 along with site elevation and each station's anemometer type and height above the ground surface. Elevations vary from 2,572 (Southgate) to 4,790 (Logan) ft abv msl. The 014A (Met One) anemometer is a cup type device whereas the 05103 (R.M Young) is a propeller type. Sensor heights are greater at Logan and Murray in an attempt to elevate the sensors above sprinkler stream heights. Weather data for all the sites (except Sunbrook) are presently available on the web at URL: http://extension.usu.edu/agweather.

TABLE 2: COORDINATES AND ELEVATIONS OF ELECTRONIC WEATHER STATIONS AT TURF LYSIMETER SITES IN UTAH

Site	Latitude	Longitude	Elevation (ft)	Elevation (m)	Anemometer Type	Anemometer Height (m)
Logan Golf and Country Club	N 41° 44.682'	W 111° 47.363'	4790	1460	014A	4
Murray Golf Course	N 40° 37.881'	W 111° 55.190'	4294	1309	014A	4
South Gate Golf Course	N 37° 04.434'	W 113° 35.414'	2572	784	05103	3
Spanish Fork	N 40° 04.031'	W 111° 37.753'	4680	1427	014A	3
Sunbrook Golf Course	N 37° 06.488'	W 113° 38.044'	2678	816	05103	3

SITE DESCRIPTIONS

Cache Valley – Logan Golf and Country Club

The golf course is situated in the mouth of Logan Canyon, on the east side of Cache Valley in Northern Utah, about 2.5 miles ENE along Highway 89 from the 400 North and Main Street intersection in Logan at an elevation of about 4790 feet. The course itself is on an old lake terrace, deposited under ancient Lake Bonneville. The soil is classified as a Ricks gravelly loam with parent material of alluvium and deltaic sediments derived from limestone, sandstone and quartzite. The lysimeter site has 6 - 12 inches of loam topsoil underlaid by gravelly loam (includes river-run gravel up to cobble size, Fig 7). Winter temperatures drop as low as 20 degrees below zero Fahrenheit, whereas summer high temperatures may reach 90 degrees Fahrenheit and above. The frost free period is 140 to 160 days. Normal (1971-2000) annual precipitation is 19.9 inches.

The lysimeters are situated on the SE side of the course close to the Logan Canyon mouth, west of the greens nursery and north of the fairway for the 3rd hole. The turf is a Merion bluegrass. The cutting height is set at 1 ½ inches in the rough, where the lysimeters are located, and at 3/4 of an inch in the fairways. The irrigation season is generally from mid-May into late September or early October. Irrigation is in 12-minute cycles up to 2 times per day, if needed. Sprinklers are placed in a 65 ft. triangular spacing with nozzle discharge of 20.5 gpm.

The first season of lysimeter data collection began in the spring of 1992 (East and West) and May 2004 (New) and has continued to the present. Data collection was initiated in the spring after snow melt and continued on into late fall or early winter, until significant snow cover. The period of measurement of turfgrass water use varied from year to year, as affected by the occurrence of snow in the spring and the fall, but was generally from mid-April to late October. Weather data from the weather station was retrieved once per week, prior to when the web site file transfer protocol (FTP) process was established.

Salt Lake County – Murray Parkway Golf Course

The golf course is located in mid Salt Lake Valley, about 0.5 miles east of the Jordan River, south of I-215 and north of Winchester Blvd (66th South) in Murray. The local area soil is classified as a Kidman very fine sandy loam with parent material of lacustrine deposits. The lysimeter site is on imported (hauled in) soil material. There are 6 - 10 inches of loam topsoil underlain by clayey gravel (up to cobble size, Fig 8). It is near the valley bottom at an elevation of about 4285 feet. Winter temperatures drop as low as 5 degrees below zero Fahrenheit, whereas summer high temperatures may reach 95 degrees Fahrenheit and above. The frost free period is 160 to 180 days. Normal (1971-2000) annual precipitation is 16 inches.

The lysimeters are situated on the south side of the course, north of the fairway for the 16th hole, about 70 feet east of the 150 yard marker, 390 feet NW of the maintenance shed and 200 feet north of the weather station. The turf is a Kentucky bluegrass and perennial ryegrass mixture. The cutting height is set at 2 inches in the rough, where the lysimeters are located, and at 3/4 of an inch in the fairways. The irrigation season is generally from early May into early October. Irrigation is in 9-minute cycles up to 3 times per day, if needed. Sprinklers are placed in a 70 ft. triangular spacing with nozzle discharge of 22.5 gpm.

The first season of lysimeter data collection began in the spring of 2002 and has continued to the present. Data collection was initiated in the spring after snow melt and continued on into late fall or early winter, until significant snow cover. The period of measurement of turfgrass water use varied from year to year, as affected by the occurrence of snow in the spring and the fall, but was generally from early April to late October. Data from the weather station was obtained from occasional site visits as well as from the web site FTP process.

Utah County – BYU Spanish Fork Farm

The BYU Agronomy turf plots are about 3 ¼ miles SSE of Spanish Fork and about ¾ mile SE of the BYU Dairy (no longer in existence). The plots are on an old lake terrace, deposited under ancient Lake Bonneville. The soil is classified as a Timpanogos loam with parent material of lacustrine deposits derived from limestone, quartzite and granite. The lysimeter site has about 24 inches of loam topsoil under lain by silt loam (Fig 9). It is located near the mouth of Spanish Fork Canyon at an elevation of about 4700 feet. Winter temperatures drop as low as 10 degrees below zero Fahrenheit, whereas summer high temperatures may reach 95 degrees Fahrenheit and above. The frost free period is 150 to 170 days. Normal (1971-2000) annual precipitation is 21.6 inches.

The lysimeters are situated about 240 yards SSW of the field shed, 180 yards SW of the weather station and about 15 feet east of a line-source sprinkler used to apply varying amounts of water to the turf plots. The turf in the plots surrounding the lysimeters is a fescue. However, the lysimeters were re-sodded with bluegrass. Cutting height was about 2 inches and the lysimeters were hand clipped to match. The irrigation season was generally from mid-May into early October. Irrigation was scheduled about once per week with the duration adjusted as needed to provide the appropriate depth of water at the lysimeters. Sprinklers were placed about 20 ft. apart along the line with nozzle discharge of 8-9 gpm.

The first season of lysimeter data collection began in the spring of 2002 and continued through 2006 when farm management changed. Data collection was initiated in the spring after snow melt and continued on into late fall or early winter, until significant snow cover. The period of measuring turfgrass water use varied from year to year, as affected by the occurrence of snow in the spring and the fall but was generally from early April to late October. Weather data from the weather station was obtained from occasional site visits as well as from the web site.

Washington County – Southgate Golf Course

The golf course is 2 miles SSW of St. George about 0.3 miles west of the I-15 crossing over the Santa Clara River. It is located along the Santa Clara River at an elevation of about 2550 feet.

The soil is classified as a Tobler fine sandy loam with parent material of alluvium derived from sandstone and shale. The reddish colored sandy soil is more than 3 feet deep (Figs 3 and 4). Wintertime temperatures are moderate although minimums drop below freezing, whereas summertime high temperatures may reach 110 degrees Fahrenheit and above. The frost free period is 210 to 240 days. Normal (1971-2000) annual precipitation is 8.8 inches.

The lysimeters are situated about in the middle of the course, about 100 yards easterly of the club house, about 200 ft from the 1st tee and about 35 to 50 feet south and east of the weather station (Fig 10). The Bermuda grass turf is over seeded by perennial ryegrass in the early fall (September). The cutting height is set at 1 ½ inches in the rough north of the fairway, where the lysimeters are located. Irrigation occurs all year with the frequency varying from daily in the summer to once every week or less frequent in the winter, depending on the occurrence of winter rains. The irrigation duration is adjusted to match ET values and specific location soil conditions across the course. Sprinklers are placed in a 70 ft. triangular spacing with nozzle discharge of 32 gpm.

The first season of lysimeter data collection began in June of 2004 and continued into mid-December 2008. Data collection continued generally year around. The period of measurement of turf-grass water use varied somewhat from year to year, as affected by personnel availability. The weather data from the weather station was obtained from occasional site visits as well as from the web site.

Washington County – Sunbrook Golf Course

The golf course is about 3 ¼ miles WNW of St. George and about 2 miles SSW of Santa Clara. It is located along the Santa Clara River at an elevation of about 2670 to 2720 feet. The soil is classified as a Tobler fine sandy loam with parent material of alluvium derived from sandstone and shale. The lysimeter site sandy loam soil is uniform and more than 3 feet deep (Fig 2). Winter temperatures are moderate although minimums drop below freezing, whereas summer high temperatures may reach 110 degrees Fahrenheit and above. The frost free period is 210 to 240 days. Normal (1971-2000) annual precipitation is 8.8 inches.

The lysimeters are situated in the north end of the driving range, which is about in the middle of the course, 270 yards north of the clubhouse, 130 feet south of the maintenance shed and about to 230 feet northeast of the weather station (Fig 11). The Kentucky bluegrass/perennial ryegrass/Bermuda grass turf is overseeded by annual ryegrass in the early fall (September). Due to herbicide effects, the lysimeters and adjacent area were re-sodded to turf type fescue mid-June 2004. The cutting height is set at 1 ½ inches where the lysimeters are located. Irrigation occurs during the night and is year round. Irrigation frequency varies from daily in the summer to once every week or less frequently in the winter, depending on the occurrence of winter rains. The irrigation duration is adjusted to match ET values and specific location soil conditions across the course. Sprinklers are placed in a 65 foot triangular spacing with nozzle discharge of 30 to 35 gpm.

The first season of lysimeter data collection began in 2002 and continued through 2006. Data collection continued generally year round. The period and consistency of measuring turfgrass water use varied somewhat from year to year, as affected by personnel availability. The weather data from the weather station was obtained from occasional site visits as well as from the web site.

Data Analysis

Weather Data

The collected weather data was analyzed and reviewed to remove errors and inaccurate or missing values. The solar radiation sensor calibration was corrected for each season by comparing observed daily total solar radiation with theoretical clear day solar radiation using the procedure described in Hill (1994) and Allen, et al. (2005). The most frequent corrections involved missing hourly data. On such occasions, values for the missing hour were estimated by averaging the values from the hours before and after the missing one. Details of the corrections or adjustments made to the weather data by site and year are given in Appendix E.

Lysimeter Data

Actual evapotranspiration (ET_a) was calculated by performing a simple water balance for each lysimeter. A summation was done for total rain plus irrigation measured in the two rain gages near each lysimeter and an average of the two values was taken to represent the rain plus irrigation which was applied over the lysimeter area. This value was added to the sum of additional water applied to the lysimeter (which was converted into an equivalent depth over the lysimeter). The sum of the equivalent drainage was subtracted from this value to obtain total ET for the calculation period (see Equation 5). An entire calculation period ET_{lys} was determined by:

$$\sum ET_{lys} = \sum(R+I) + \sum W_{added} - \sum D \qquad (6)$$

where ET_{lys} is lysimeter estimated evapotranspiration (in), R is rain (in), I is irrigation (in), W_{added} is water added (in) and D is drainage (in).

The measured bucket drainage depth was converted into an equivalent depth, by:

$$D = \frac{\pi h_{avg}}{8 A_{lys}} \left[\left(d_{bottom} + h_{avg} \left(\frac{d_{bottom} - d_{top}}{h_{bucket}} \right) \right)^2 + \left(d_{bottom} \right)^2 \right] \qquad (7)$$

where D is the equivalent depth of drainage over the lysimeter (in), h_{avg} is the average height of water in the drainage bucket (in), A_{lys} is the area of the lysimeter (1600 sq in), D_{top} is diameter of the top of the bucket (in), D_{bottom} is diameter of the bottom of the bucket (in) and h_{bucket} is height of the bucket (in).

Daily Soil Water Balance Model

On a number of occasions for nearly all of the sites the drainage buckets were observed to have overtopped between visits. Such an event causes a loss of data because the exact volume of drainage is not known. In order to obtain a reasonable estimation of the actual drainage on these occasions a model was developed in Visual Basic. The model performed running soil water balance for each day during the calculation period from which it calculated daily deep percolation (DP) (see Equation 6). The first reading was ignored by the program since the total precipitation which resulted in the initial drainage reading was not known.

The daily soil water balance model is represented by:

$$DP_i = (SW_1)_i - (SW_2)_i + (R + I)_i + (W_{added})_i - K_c(ET_{rs})_i \quad (8)$$

where DP_i is deep percolation (in), $(SW_1)_I$ is the initial soil water content for the current day (in), note that $(SW_1)_i = (SW_2)_{i-1}$ $(SW_2)_I$ is the final soil water content for the current day (in), $(R + I)_i$ is the rain plus irrigation observed for current the day (in), $(W_{added})_I$ is the water added to the lysimeter on the current day (in), K_c is the crop coefficient determined by the user (decimal) and $(ET_{rs})_I$ is the ASCE standardized reference evapotranspiration (in).

Input for the model was a comma delineated file containing the sum of the hourly calculated ET_{rs} for each day as well as the lysimeter readings for each observation. A reasonable full season crop coefficient was input into the model as well as an available water content of the soil in the lysimeter (AW) and the initial soil water content as estimated for the calculation period (SW_0). The SW_0 was assumed to be equal to the AW for nearly all of the lysimeters each year. This assumption was justified because typically a calculation period began early in the year and drainage was often observed on the first observation, meaning that the soil water content was at field capacity at that time.

Values of soil parameters, AW and SW_0 used for the calculations performed by the soil water balance model are given in Table 3. The SW_0 value at Murray for 2003 was assumed to be half of the AW, because no or little drainage was observed at either lysimeter for the entire season (0 inches at the East and 0.03 inches at the West). This was needed in order to obtain reasonable results from the model.

TABLE 3: AVAILABLE WATER CONTENT AND INITIAL SOIL WATER CONTENTS USED IN THE SOIL WATER BALANCE MODEL

Location		**AW (in)**	**SW_0 (in)**
Logan Golf and Country Club	East & West	2.6	2.6
	New	3.2	3.2
Murray Golf Course*		4.6	4.6
South Gate Golf Course		2.4	2.4
Spanish Fork		4.6	4.6
Sunbrook Golf Course		3.0	3.0

* The SW_0 for both lysimeters at Murray GC in 2003 was set to 2.3 in.

The model could be used to calculate the mean crop coefficient for the season if there were no problems with overtopped drainage buckets, or if these events had been adjusted from previous runs of the model. The K_c value could be determined if the input K_c value were adjusted until the calculated deep percolation was equal to the measured, or adjusted, drainage. This provided K_c values which could be used to verify the values obtained by the method described in Equations 5 and 6. The model estimates drainage based on a soil water balance, for those days when a drainage bucket spilled over top (and thus lost data). This estimated drainage value was then inserted into the data file and the model was run again. The K_c values were obtained using the adjusted drainage values. A description of the adjustments is given in Appendix F.

RESULTS AND DISCUSSION

Observation and Calculation Periods

The period for which consumptive use calculations were performed each year varied from location to location and were not always continuous throughout the growing season. The beginning and ending dates of weather and lysimeter data collection and the calculation periods for Logan, Murray, Spanish Fork, Southgate and Sunbrook, are given in Tables 4 through 8, respectively.

Full calendar year weather data was available for nearly every location and year of the study with the following exceptions: January 1 through March 31, 2006 was omitted at Murray due to errors in the data, Southgate data began on June 23, 2004 and Sunbrook data began on February 22, 2002 (Tables 5, 6, and 8).

The calculation period and observation period for lysimeter data at the Logan golf course are the same every year except 2004 and 2006 (Table 4). The new lysimeter at Logan was installed on April 7, 2004. For this purpose the calculation period for that year began on May 7. The calculation period began on April 26, 2006 due to some inconsistencies in the data collected on April 19 for the West lysimeter; therefore the first two readings were neglected.

Table 4: Logan Golf and Country Club beginning and ending dates for data Collection and calculation periods

Year	Weather				Lysimeter				Calculation Period			
	Begin Day		End Day		Begin Day		End Day		Begin Day		End Day	
	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day
2002	1-Jan	1	31-Dec	365	25-Mar	84	14-Oct	287	25-Mar	84	14-Oct	287
2003	1-Jan	1	31-Dec	365	17-Mar	76	13-Oct	286	17-Mar	76	13-Oct	286
2004*	1-Jan	1	31-Dec	366	27-Mar	87	18-Oct	292	7-May	127	18-Oct	292
2005	1-Jan	1	31-Dec	365	15-Mar	74	24-Nov	328	15-Mar	74	24-Nov	328
2006	1-Jan	1	31-Dec	365	14-Apr	104	8-Nov	312	26-Apr	116	8-Nov	312
2007	1-Jan	1	31-Dec	365	5-Apr	95	17-Nov	321	5-Apr	95	17-Nov	321

* The new lysimeter was installed on April 7, 2004. This is the reason the calculation period began on May 7.

The only year at Murray which had a calculation period differing from the lysimeter data period of record was 2005 (Table 5). This was because of an abnormally large precipitation event on April 4. This event caused skewed results and thus the data was not included for the previous weeks or the following two weeks in order to insure a more typical situation.

TABLE 5: MURRAY PARKWAY GOLF COURSE BEGINNING AND ENDING DATES FOR DATA COLLECTION AND CALCULATION PERIODS

Year	Weather				Lysimeter				Calculation Period			
	Begin Day		End Day		Begin Day		End Day		Begin Day		End Day	
	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day
2002	1-Jan	1	31-Dec	365	4-May	124	14-Oct	287	4-May	124	14-Oct	287
2003	1-Jan	1	31-Dec	365	15-Apr	105	13-Oct	286	15-Apr	105	13-Oct	286
2004	1-Jan	1	31-Dec	366	29-Mar	89	15-Nov	320	29-May	89	15-Nov	320
2005	1-Jan	1	31-Dec	365	7-Mar	66	26-Sep	269	25-Apr	115	19-Sep	262
2006	1-Apr	91	31-Dec	365	20-Mar	79	25-Sep	268	20-Mar	79	25-Sep	268
2007	1-Jan	1	31-Dec	365	2-Apr	92	19-Nov	323	2-Apr	92	19-Nov	323

The calculation period for Southgate Golf Course began on June 11, 2004 (Table 6), which was about a week after installation. However, the weather station was not installed until June 22. The weather data for June 11 through June 22 was obtained from the station at Sunbrook Golf Course. This was justified because of the proximity of the two weather stations (approximately 3.4 miles apart) and the observation that data from the two locations was quite similar. In 2006 there was a break in data collection due to changes in personnel at both Southgate and Sunbrook; this is the reason for the late beginning date for the calculation period.

TABLE 6: SOUTHGATE GOLF COURSE BEGINNING AND ENDING DATES FOR DATA COLLECTION AND CALCULATION PERIODS

Year	Weather				Lysimeter				Calculation Period			
	Begin Day		End Day		Begin Day		End Day		Begin Day		End Day	
	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day
2004	23-Jun	174	31-Dec	366	9-Apr	100	4-Dec	339	11-Jun	162	4-Dec	339
2005	1-Jan	1	31-Dec	365	10-Mar	69	2-Dec	336	10-Mar	69	2-Dec	336
2006	1-Jan	1	31-Dec	365	23-Jan	23	1-Dec	335	23-Jun	23	1-Dec	335
2007	1-Jan	1	31-Dec	365	24-Jan	24	29-Dec	363	24-Jan	24	29-Dec	363

The only years at Spanish Fork with calculation periods shorter than the period of record for the lysimeters, were 2002 and 2003 (Table 7). In 2002 water was added to both lysimeters on May 20. The lysimeters had been installed the previous month and had most likely not completely settled. The results seemed much more appropriate when the weeks effected by the water addition on May 20 were eliminated. In 2003 there was a late spring snowfall event on April 8, which causes inaccurate precipitation readings. Thus, the beginning date for the calculations was changed to April 30.

TABLE 7: SPANISH FORK BEGINNING AND ENDING DATES FOR DATA COLLECTION AND CALCULATION PERIODS

Year	Weather				Lysimeter				Calculation Period			
	Begin Day		End Day		Begin Day		End Day		Begin Day		End Day	
	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day
2002	1-Jan	1	31-Dec	365	10-May	130	3-Oct	276	5-Jun	156	3-Oct	276
2003	1-Jan	1	31-Dec	365	17-Mar	76	10-Nov	314	30-Apr	120	10-Nov	314
2004	1-Jan	1	31-Dec	366	1-Apr	92	10-Nov	315	1-Apr	92	10-Nov	315
2005	1-Jan	1	31-Dec	365	22-Mar	81	2-Nov	306	22-Mar	81	2-Nov	306
2006	1-Jan	1	31-Dec	365	24-Apr	114	11-Oct	284	24-Apr	114	11-Oct	284

A number of data collection problems occurred at Sunbrook Golf Course. The only years for which the calculation period matched the lysimeter period of record were 2004 and 2005 (Table 8). In 2002 the weather station was not installed until February 22, so the calculation period began at the next lysimeter observation (February 25). Data collection was sporadic during January 2003, therefore the calculation period begins on February 3. In 2006 there was a large gap in the lysimeter data between March 29 and June 26, so data previous to this gap was excluded from the study.

TABLE 8: SUNBROOK GOLF COURSE BEGINNING AND ENDING DATES FOR DATA COLLECTION AND CALCULATION PERIODS

Year	Weather				Lysimeter				Calculation Period			
	Begin Day		End Day		Begin Day		End Day		Begin Day		End Day	
	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day	Date	Day
2002	22-Feb	53	31-Dec	365	7-Jan	7	5-Nov	309	25-Feb	56	5-Nov	309
2003	1-Jan	1	31-Dec	365	2-Jan	2	10-Nov	314	3-Feb	34	10-Nov	314
2004	1-Jan	1	31-Dec	366	1-Mar	61	21-Sep	265	1-Mar	61	21-Sep	265
2005	1-Jan	1	31-Dec	365	18-Jan	18	28-Dec	362	18-Jan	18	28-Dec	362
2006	1-Jan	1	31-Dec	365	5-Jan	5	16-Oct	289	26-Jun	177	16-Oct	289

WEATHER DATA ADJUSTMENTS AND CALCULATED REFERENCE EVAPOTRANSPIRATION

Solar radiation sensor calibration correction factors for each site and year are given in Table 9. A correction factor less than one indicates that recorded solar radiation sensor values are higher than what would have been obtained from a field sensor with the correct calibration programmed into the datalogger. Correction factors varied from 0.969 (Murray, 2007) to 1.087 (Spanish Fork, 2004). This indicates that field sensor values varied from about 3% high to 9% low. The sensors at Logan and Murray generally required lesser adjustments after the fact than sensors at other sites. The calculation time steps, hourly or daily, that were possible at each site are also given in Table 9. Generally, data from the year 2002 were stored only at 2 hour intervals, thus hourly calculations were not feasible. Beginning with 2003, all dataloggers, except at Spanish Fork, were programmed for hourly data storage, which facilitated hourly as well as daily time step calculations.

TABLE 9: SOLAR RADIATION CALIBRATION FACTOR AND ET_R CALCULATION TIME STEP FOR EACH SITE AND YEAR AT UTAH TURF LYSIMETER SITES, 2002-2008.

Site	Year	Rs Calibration Factor	Calculation Time Step	Comments
Logan	2002	1.025	Daily[a]	Hourly parameters not saved
	2003[b]	1.012	Hourly	
	2004	1.010	Hourly	
	2005	1.006	Hourly	
	2006	1.002	Hourly	
	2007	1.004	Hourly	
	2008	0.997	Hourly	
Murray	2002	0.994	Daily	Hourly parameters not saved
	2003 [b]	0.978	Hourly	
	2004	0.986	Hourly	
	2005	0.987	Hourly	
	2006 [b]	0.971	Hourly	
	2007 [b]	0.969	Hourly	
	2008 [b]	0.979	Hourly	
Southgate	2004 [b]	1.048	Hourly	
	2005	1.032	Hourly	
	2006	1.049	Hourly	
	2007	1.017	Hourly	
	2008	1.048	Hourly	
Spanish Fork	2002[c]	0.980/1.086	Daily	Climate Center station had bad RH, daily dew point limit was used
	2003	1.086	Daily	Hourly parameters not saved
	2004	1.087	Daily	Hourly parameters not saved
	2005	1.081	Daily	Hourly parameters not saved
	2006	1.070	Hourly	
Sunbrook	2002 [b]	1.045	Daily	Hourly parameters not saved
	2003 [b]	1.078	Hourly	
	2004	1.084	Hourly	
	2005	1.068	Hourly	
	2006	1.082	Hourly	
	2007	1.070	Hourly	

[a] A wind limit of 110 miles/day was used for the daily calculations for Logan in 2002. This wind limit was based on calculations for 2003 to 2008 hourly and daily ETr calculations using different daily wind limits.

[b] Partial year of data as follows: Logan 2003 = 1 Feb to 31 Dec, Murray 2003 = 1 Feb to 21 Dec, Murray 2006 = 1 Apr to 31 Dec, Murray 2007 = 1 Jan to 28 Nov, Murray 2008 = 26 Jan to 31 Dec, Southgate 2004 = 23 Jun to 31 Dec, Sunbrook 2002 = 22 Feb to 31 Dec, Sunbrook 2003 = 29 Jan to 31 Dec.

[c] Spanish Fork 2002 includes data from a Utah Climate Center weather station through day 234, data for the remainder of the year was measured by the current weather station. Only daily calculations were performed, dew point was set to be no more than 4°F below Tmin in the Climate Center station daily calculations. Spanish Fork 2002 has two Rs calibrations, one for the Climate Center station and one for the current station. Calculations for 2002 were done using the CRPSMW model.

A comparison of ASCE Standardized Penman-Monteith tall crop (alfalfa) reference ET (ET_{rs}) values calculated using both daily and hourly time steps is given in Table 10 for the five turf lysimeter sites in Utah.   As noted above, only daily calculation time steps were possible in 2002 and at Spanish Fork (except for 2006). Two sets of wind and ET_{rs} values are shown in Table 10. The first, denoted "Original" wind run or speed, was made from the original recorded wind travel and speed, whereas the other calculation of ET_{rs} was made with "Adjusted" wind data. A temporary co-location of electronic weather stations with both cup type (Met One 014A) and propeller type (R.M. Young 05103) anemometers was made in the Snowville area as part of another research study. As a result, we discovered that the cup type anemometers (014A) give higher wind velocities than the propeller type (05103). Further calibration checks against a CSAT3 sonic anemometer confirmed that the 014A read high and the 05103 low. Only Southgate and Sunbrook (Table 2) have the propeller type. This infers that ET_{rs} for Southgate and Sunbrook would be relatively lower due to the underestimated wind speeds. Thus, the calculated crop coefficient, with unadjusted wind speed, would be higher than it should be. The converse is the case for the other sites (Logan, Murray and Spanish Fork).

Inspection of Table 10 indicates that the "Original" average wind travel at Logan and Murray is about 170 and over 125 miles per day (mpd), respectively, and is about 100 mpd at Spanish Fork. Wind travel at Southgate and Sunbrook averages considerably less at about 50 and 60 mpd, respectively. The corresponding daily time step calculated average annual ET_{rs} is about 79 inches at Logan, and 64, 58, 64 and 70 inches, respectively, at Murray, Southgate, Spanish Fork and Sunbrook. This illustrates the sensitivity of the ASCE Standardized penman-Monteith, indeed any Penman combination type ET equation, to wind speed (or wind travel). The high ET_{rs} at Logan, compared with the considerably warmer southern Utah sites is somewhat counterintuitive. However, hourly time step calculated average annual ET_{rs} is lower than the daily time step ET_{rs} value at sites with the higher wind travel, i.e. Logan (61 in. vs. 79), Murray (63 in. vs. 64) and Spanish Fork (62 in. vs. 64).   Hourly calculated ET_{rs} is higher than daily ET_{rs} at the lower wind sites of Southgate (62 in. vs. 58) and Sunbrook (71 in. vs. 70).

Imposing the "Adjusted" wind reduces the ET_{rs} values for the sites with cup type anemometers (Logan, Murray and Spanish Fork) while increasing calculated ET_{rs} at Southgate and Sunbrook, both sites with lower average wind (Table 10) and propeller anemometers. The net effect of wind adjustment for the high wind sites (cup anemometers) was about a 12% drop in wind travel (Table 10). Wind travel increased about 23% at the relatively low wind sites (Southgate and Sunbrook) with the adjustment.

The effect of the wind adjustment on ETrs was less pronounced. Annual ETrs, daily time step calculation, averaged 5% less at the three cup anemometer (014A) high wind sites and 10% more at the two propeller anemometer (05103) low wind sites as a result of the wind adjustment compared to using the original reported wind. Similarly, hourly calculated ETrs averaged 4% less at the cup anemometer (014A) sites and 6% more at the propeller anemometer (05103) sites.

TABLE 10: COMPARISON OF DAILY AND HOURLY CALCULATED ET_{RS} VALUES WITH AND WITHOUT WIND ADJUSTMENTS FOR EACH SITE AND YEAR AT UTAH TURF LYSIMETER SITES, 2002-2008.

Site	Year	Calculations Using Daily Time Step				Calculations Using Hourly Time Step			
		Average Daily Wind Run (mpd)		Annual ET_{rs} With Original Wind (inches)	Annual ET_{rs} With Adjusted Wind (inches)	Average Wind Speed (mph)		Annual ET_{rs} With Original Wind (inches)	Annual ET_{rs} With Adjusted Wind (inches)
		Orig	Adj	ASCE Std. PM	ASCE Std. PM	Orig	Adj	ASCE Std. PM	ASCE Std. PM
Logan	2002†	173	156	77.02	74.04	-----	-----	-----	-----
	2003*	185	168	81.80	78.63	7.69	6.99	62.08	60.07
	2004	166	150	74.14	71.31	6.93	6.26	57.97	56.22
	2005	162	146	74.55	71.67	6.76	6.09	58.07	56.29
	2006	178	162	79.78	76.64	7.43	6.74	61.03	59.03
	2007	171	154	84.01	80.61	7.11	6.43	65.30	63.09
	2008	170	154	78.85	75.68	7.09	6.41	60.10	58.08
	Average	172	156	78.59	75.51	7.17	6.49	60.76	58.80
Murray	2002†	125	110	67.82	64.30	-----	-----	-----	-----
	2003*	128	113	66.59	63.08	5.34	4.70	65.70	63.12
	2004	122	107	64.11	60.94	5.10	4.47	63.53	61.24
	2005	128	113	64.24	61.09	5.33	4.70	62.57	60.35
	2006*	124	109	57.78	54.81	5.15	4.52	56.29	54.12
	2007*	125	110	68.81	65.21	5.22	4.60	67.81	65.17
	2008*	121	106	61.01	57.68	5.01	4.38	59.68	57.23
	Average	125	110	64.34	61.02	5.19	4.56	62.60	60.21
Southgate	2004*	45	58	33.47	37.20	1.89	2.43	36.31	38.97
	2005	44	57	60.47	67.06	1.84	2.38	65.84	70.47
	2006	51	64	64.38	70.94	2.14	2.67	68.49	73.08
	2007	54	67	67.13	73.89	2.24	2.77	71.67	76.48
	2008	52	65	65.16	71.68	2.18	2.71	69.50	74.04
	Average	49	62	58.12	64.15	2.06	2.59	62.36	66.61
Spanish Fork	2002**	107	93	64.34	59.84	-----	-----	-----	-----
	2003‡	79	65	63.99	58.86	-----	-----	-----	-----
	2004‡	94	80	61.91	57.87	-----	-----	-----	-----
	2005‡	97	83	62.59	58.66	-----	-----	-----	-----
	2006	102	88	66.11	61.94	4.27	3.67	61.76	59.06
	Average	96	82	63.79	59.43	4.27	3.67	61.76	59.06
Sunbrook	2002*†	71	83	70.31	76.25	-----	-----	-----	-----
	2003*	65	78	70.71	76.88	2.80	3.33	71.05	74.94
	2004	65	78	71.19	77.25	2.72	3.24	72.29	76.16
	2005	60	73	66.53	72.53	2.51	3.03	67.86	71.66
	2006	62	75	68.45	74.89	2.60	3.12	69.05	73.29
	2007	62	75	70.00	76.59	2.60	3.13	72.84	77.38
	Average	64	77	69.53	75.73	2.65	3.17	70.62	74.69

†In 2002 Logan, Murray, and Sunbrook did not record necessary parameters for ETr calculations on an hourly time step

* Partial year of data, see Table 9 footnote b.

** See Table 9 footnote c.

‡ Spanish Fork 2002 had output every hour, however daily calculations were done for the Utah Climate Center station data, 2003 through 2005 had output every 2 hours.

LYSIMETER WATER BALANCE AND CALCULATED K_{CR} VALUES

Lysimeter water balance and calculated crop coefficients were determined for each year at each site for the period of calculation as listed in Tables 4 through 8. An estimate of actual (measured) ET_a was made from the lysimeter water balance. For the 2007 annual report seasonal turfgrass ET crop coefficients (alfalfa reference, ET_r) were estimated using daily and hourly calculation time steps for ET_r from the ASCE standardized Penman Monteith ($ASCE_{st}$ PM) and the 1982 Kimberly Penman Combination (1982 Kim Pen) Equations. The following discussion and figures were adapted from that annual report.

Comparisons of cumulative calculated ET_r and the season progression of accumulated lysimeter water use and corresponding K_c values throughout the seasons are illustrated in Figures 7, 8, and 9, respectively, for Logan, Murray, and Southgate. The difference in ET between the two old lysimeters (East and West) and the new lysimeter at Logan is particularly evident in Figure 7a. There was more difference between the estimated ET for the two lysimeters at Southgate (Figure 9) than at Murray (Figure 8).

The sum of calculated hourly ET_r was lower than the daily time step ET_r sum, except at Southgate (Figure 9a). The most dramatic difference is at Logan (Figure 7a) where the hourly ASCEst PM ET_r was 24% less than the daily calculated value. This is attributed to the high nighttime canyon winds at Logan. Generally, the $ASCE_{st}$ PM ET_r values were higher than the ET_r of the 1982 Kim Pen.

Early in the study, attempts were made to calculate weekly crop coefficient values with the assumption that the K_c value may be a bit lower in the early spring than during the summer. The results were extremely erratic with calculated K_c varying from over 2 to negative values in successive weeks. This effect is somewhat illustrated in Figure 9b where the cumulative lysimeter crop coefficient fluctuates from 0.85 down to about 0.6 and then increases again in successive calculation periods in the early season. This may be the result of a timing mismatch between weekly measurements and the occurrence of rain, irrigation and subsequent drainage. It is also an artifact of the calculation procedure which does not account for soil water depletion and subsequent refill, because soil water content was not measured. Similarly, the addition of extra water to the Murray lysimeter caused a "jump" in the calculated ET and in the crop coefficient (Figure 8).

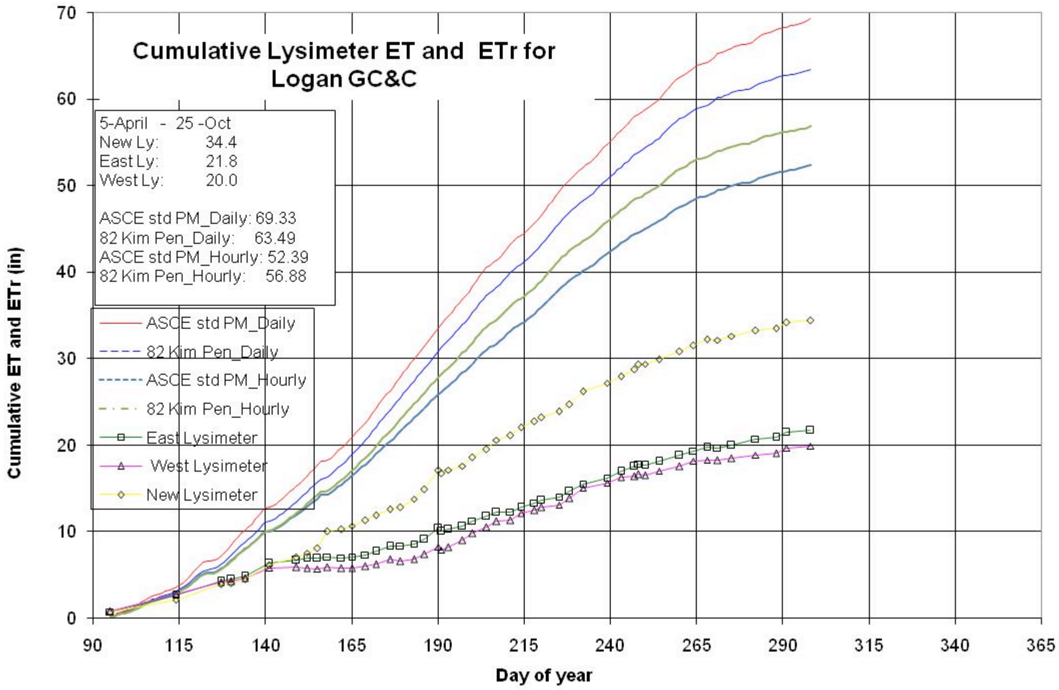

FIGURE 7A. CUMULATIVE LYSIMETER ET AND ETR FOR LOGAN GOLF AND COUNTRY CLUB, LOGAN, UTAH, 2007

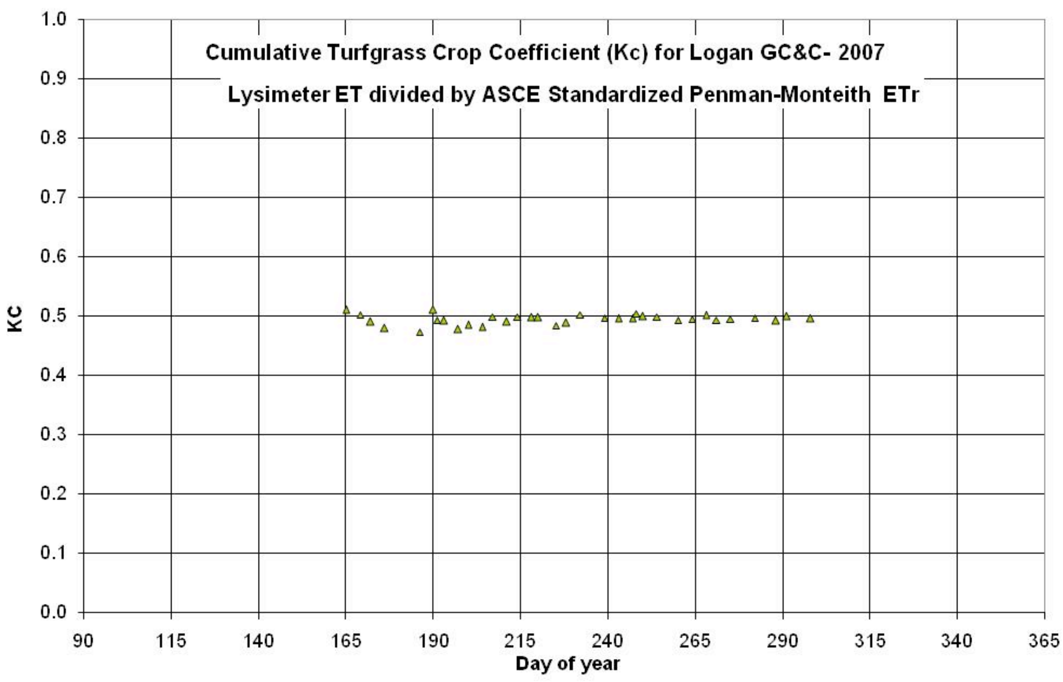

FIGURE 7B. CUMULATIVE LYSIMETER CROP COEFFICIENT FOR LOGAN GOLF AND COUNTRY CLUB, LOGAN, UTAH, 2007

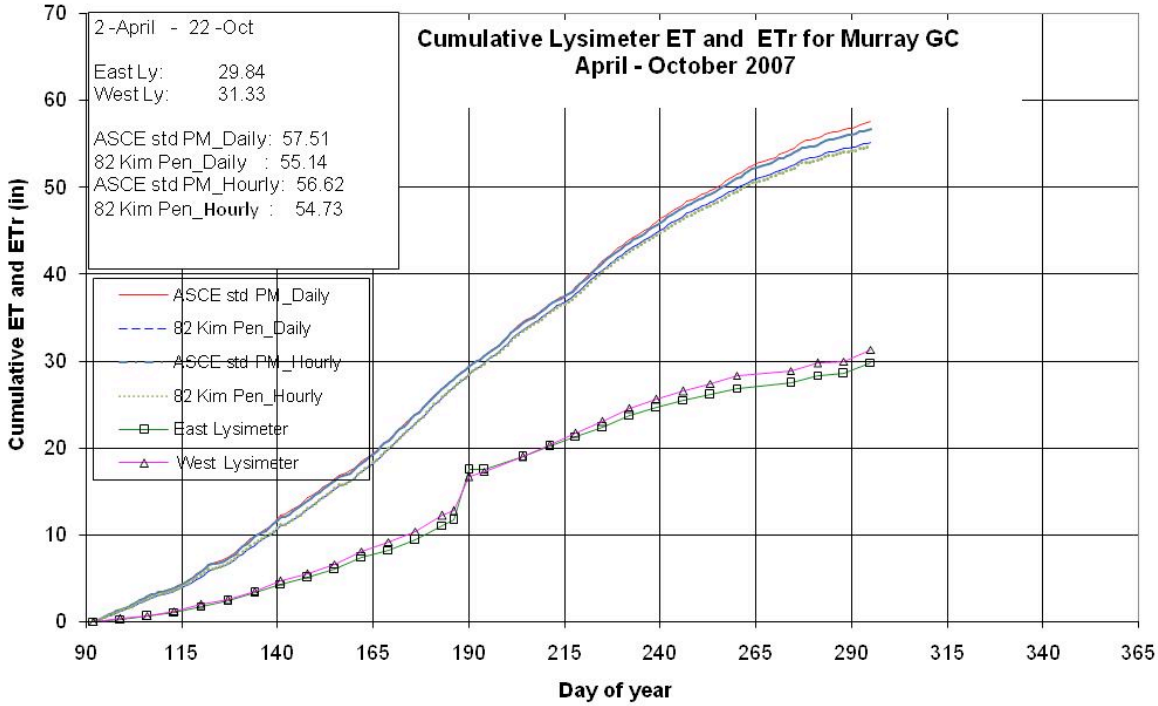

FIGURE 8A. CUMULATIVE LYSIMETER ET AND ET_R FOR MURRAY PARKWAY GOLF COURSE, MURRAY, UTAH, 2007

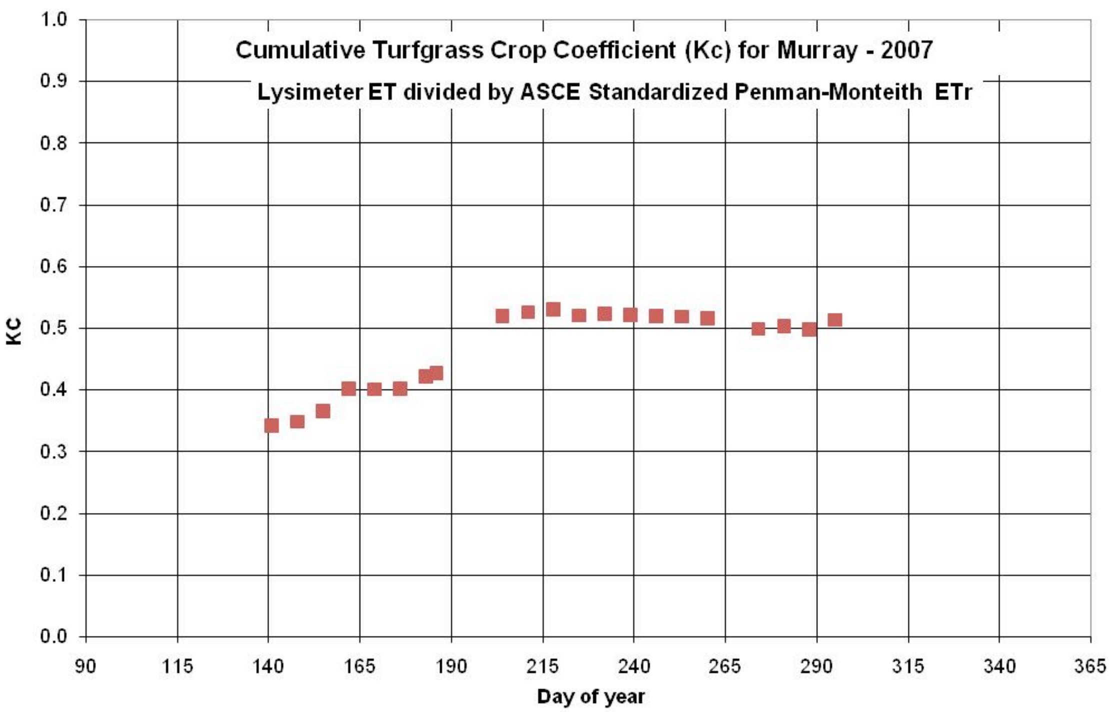

FIGURE 8B. CUMULATIVE LYSIMETER CROP COEFFICIENT FOR MURRAY PARKWAY GOLF COURSE, MURRAY, UTAH, 2007

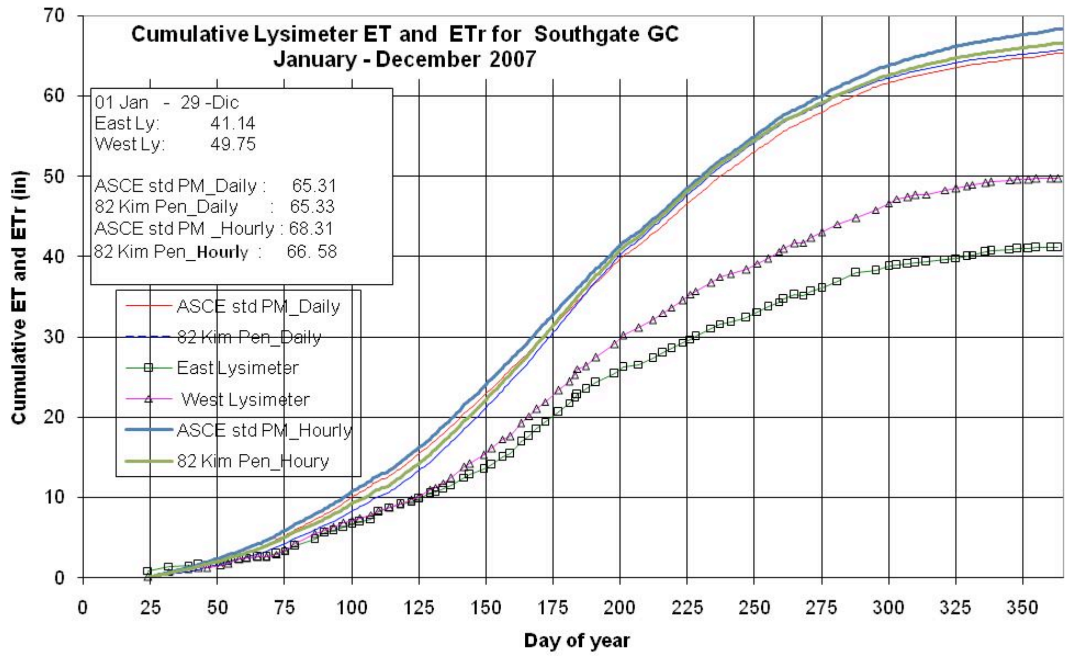

FIGURE 9A. CUMULATIVE LYSIMETER ET AND ET_R FOR SOUTHGATE GOLF COURSE, ST. GEORGE, UTAH, 2007

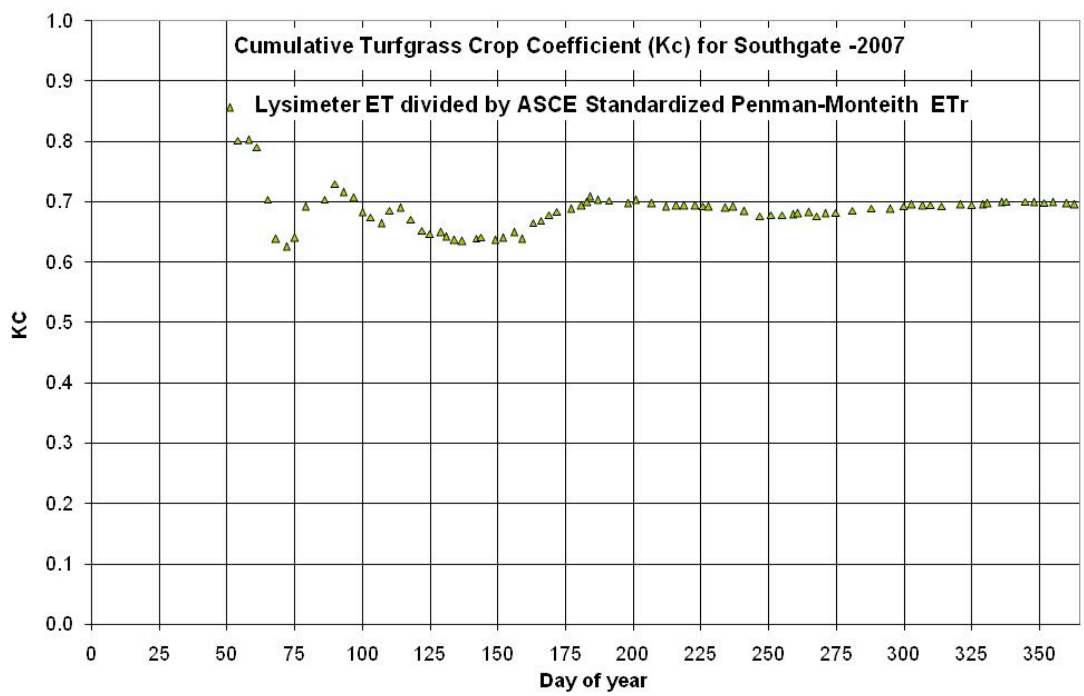

FIGURE 9B. CUMULATIVE LYSIMETER CROP COEFFICIENT FOR SOUTH GATE GOLF COURSE, ST. GEORGE, UTAH, 2007

As a result of considerations mentioned above, the ASCE Standardized Penman-Monteith Equation was used with an hourly calculation time step herein to estimate ET_r (denoted ET_{rs}). Crop coefficient (K_c) values were obtained by dividing the measured season total ET_a by the corresponding ET_{rs}. Both the actual measured drainage, in the records, and an adjusted drainage value are reported in the following tables. The adjusted drainage (see Appendix F) was obtained from using a reasonable provisional crop coefficient in the soil water balance (drainage) model.

Logan

Water balance values for the three lysimeters at Logan are given in Table 11. The new lysimeter ET varied from 21.6 (2004) to 35.2 inches (2007) and the calculated K_c varied from 0.51 to 0.66, with a 5-year average of 0.59. The East lysimeter ET varied from 14.5 (2004) to 30.3 inches (2002) and K_c varied from 0.33 to 0.61, with a 7-year average of 0.42. The West Lysimeter ET was somewhat lower, varying from 11.2 (2004) to 21.2 inches (2007) and K_c varied from 0.27 to 0.44, with a 7-year average of 0.34. Calculated hourly time step with adjusted wind ET_{rs} varied from 41.3 to 54.8 inches. Drainage adjustments were made to the 2004 and 2005 data on new lysimeter and every year on the older lysimeters, except for 2004 on the East lysimeter.

The new (East) lysimeter was installed in 2004 because of the seemingly low K_c values obtained from the two older lysimeters (particularly the West lysimeter), which were installed in 1991, in comparison with 2002 and 2003 data from other sites. Data collection on the new (which is east of the old East) lysimeter began in early May 2004 (Tables 4 and 11). The difference in estimated ET among the Logan lysimeters is clearly evident in comparing ET_a and K_c values from the new lysimeter with the West lysimeter (Table 11) and somewhat with the East lysimeter (after 2003). Considering only the new lysimeter data would suggest using an average K_c value of about 0.6 for turfgrass, which is about 7% higher than the previously used value of 0.56 (Hill, 1994).

Murray

Turfgrass water use on the Murray East lysimeter (Table 12) varied from 22.2 (2008) to 30.5 inches (2005). Calculated ET_{rs} varied from 41.5 to 56.8 inches. Estimated K_c for the East lysimeter varied from 0.46 to 0.74, with a 7-year average of 0.57. The West lysimeter ET was similar, varying from 23.2 (2007) to 30.2 inches (2007). The observed K_c varied from 0.43 to 0.70, with a 7-year average of 0.57. The average K_c for all years over both lysimeters was 0.57. The value of 0.57 for the average K_c is almost identical to the crop coefficient value (0.56) used in previous estimates of turf ET.

TABLE 11: LOGAN GOLF AND COUNTRY CLUB NEW, EAST AND WEST LYSIMETER FULL SEASON WATER BALANCE VALUES WITH SEASONAL CALCULATED CROP COEFFICIENTS

Year	Calc. Period Begin	Calc. Period End	Irrig. + Rain (in)	Water Added (in)	Measured Drain. (in)	Adjusted Drain. (in)	ET (in)	ET_{rs} (in)	K_c
New Lysimeter									
2004	7-May	18-Oct	26.07	0	4.19	4.45	21.62	40.06	0.54
2005	15-Mar	24-Nov	36.13	0	8.00	9.71	26.42	52.23	0.51
2006	26-Apr	8-Nov	33.51	2.87	5.14	5.14	31.24	47.43	0.66
2007	5-Apr	17-Nov	36.67	1.73	3.12	3.19	35.21	54.80	0.64
2008	30-Apr	21-Nov	29.89	1.73	4.17	4.20	27.42	47.31	0.58
								Average K_c =	0.59
								K_c St. Dev. =	0.07
East Lysimeter									
2002	25-Mar	14-Oct	45.03	0	13.91	14.69	30.34	50.01	0.61
2003	17-Mar	13-Oct	38.05	0	9.80	9.80	28.25	52.82	0.53
2004	7-May	18-Oct	23.14	0	8.65	8.65	14.49	40.06	0.36
2005	15-Mar	24-Nov	34.11	0	12.88	13.75	20.36	52.23	0.39
2006	26-Apr	8-Nov	29.49	0	11.86	13.03	16.46	47.43	0.35
2007	5-Apr	17-Nov	31.55	0.87	9.80	10.89	21.53	54.80	0.39
2008	30-Apr	21-Nov	24.37	0	7.76	8.63	15.74	47.39	0.33
								Average K_c =	0.42
								K_c St. Dev. =	0.10
West Lysimeter									
2002	25-Mar	14-Oct	39.30	0	13.86	20.33	18.97	50.01	0.38
2003	17-Mar	13-Oct	34.13	0	13.29	13.53	20.60	52.82	0.39
2004	7-May	18-Oct	25.21	0	13.04	14.06	11.15	40.06	0.28
2005	15-Mar	24-Nov	36.13	0	19.99	22.22	13.91	52.23	0.27
2006	26-Apr	8-Nov	32.80	0	14.83	16.51	16.29	47.43	0.34
2007	5-Apr	17-Nov	33.69	0.58	12.93	13.03	21.24	54.80	0.39
2008	30-Apr	21-Nov	31.91	0	9.64	11.08	20.83	47.39	0.44
								Average K_c =	0.35
								K_c St. Dev. =	0.06
Site Average								Average K_c for all lysimeters =	0.44
								K_c St. Dev. for all lysimeters =	0.12

TABLE 12: MURRAY PARKWAY GOLF COURSE EAST AND WEST LYSIMETER FULL SEASON WATER BALANCE VALUES WITH SEASONAL CALCULATED CROP COEFFICIENTS

East Lysimeter									
Year	**Calc. Period**		**Irrig. + Rain (in)**	**Water Added (in)**	**Measured Drain. (in)**	**Adjusted Drain. (in)**	**ET (in)**	**ET_{rs} (in)**	**K_c**
	Begin	**End**							
2002	4-May	14-Oct	28.6	0	0	0	28.60	44.65	0.64
2003	15-Apr	13-Oct	26.15	2.17	0	0	28.32	48.75	0.58
2004	29-May	15-Nov	30.11	1.73	3.58	3.58	28.26	53.08	0.53
2005	25-Apr	26-Sep	24.31	9.09	2.89	2.89	30.51	41.46	0.74
2006	20-Mar	25-Sep	23.96	6.79	2.58	6.34	24.41	46.14	0.53
2007	2-Apr	19-Nov	26.65	4.33	0.64	3.15	27.83	56.75	0.49
2008	2-Apr	19-Nov	22.57	0	0.35	0.35	22.22	48.03	0.46
								Average K_c =	0.57
West Lysimeter								K_c St. Dev. =	0.09
Year	**Calc. Period**		**Irrig. + Rain (in)**	**Water Added (in)**	**Measured Drain. (in)**	**Adjusted Drain. (in)**	**ET (in)**	**ET_{rs} (in)**	**K_c**
	Begin	**End**							
2002	4-May	14-Oct	28.80	0	0	0	28.80	44.65	0.65
2003	15-Apr	13-Oct	27.59	2.17	0.03	0.03	29.73	48.75	0.61
2004	29-May	15-Nov	30.98	0	3.02	3.02	27.96	53.08	0.53
2005	25-Apr	26-Sep	24.80	6.06	1.78	1.78	29.08	41.46	0.70
2006	20-Mar	25-Sep	26.73	3.47	2.75	3.89	26.31	46.14	0.57
2007	2-Apr	19-Nov	29.32	2.60	0.14	1.73	30.19	56.75	0.53
2008	2-Apr	19-Nov	23.59	0	0.36	0.36	23.23	54.03	0.43
								Average K_c =	0.57
								K_c St. Dev. =	0.09
Site Average								Average K_c for all lysimeters =	0.57
								K_c St. Dev. for all lysimeters =	0.09

The Murray superintendent used a K_c of 0.56 as a guide in irrigation scheduling. As noted earlier, the irrigation amount at Murray is moderated to avoid creating or worsening a troublesome wet spot in a heavy traffic area toward the end of the 16th fairway. As a result the estimated turf ET was essentially the same as irrigation plus rainfall. Thus, the similarity between K_c values may not be coincidental. Because of the slightly deficit irrigation, very few drainage events occurred for each calculation period at Murray; thus any abnormal drainage had a significant effect on the calculated crop coefficient. This was evident in 2005, where the calculated K_c values are considerably higher than the values calculated for other years. Drainage adjustments were made in 2006 and 2007 on both lysimeters.

Southgate

Evapotranspiration estimated from water balance values at Southgate varied from 19.7 (2006) to 40.2 inches (2007) for the East lysimeter and from 23.1 (2006) to 50.0 inches (2007) on the West (Table 13). Calculated ET_{rs} for Southgate varied from 36.9 to 74.7 inches. Estimated K_c for the East lysimeter varied from 0.48 to 0.55, with a 5-year average of 0.53. The West lysimeter K_c was somewhat higher, varying from 0.63 to 0.67, with a 5-year average of 0.65. Average K_c for all years over both lysimeters was 0.59. Drainage adjustments were made every year except 2006 on the East lysimeter and 2004 on the West.

For reasons that are not clear, ET on the West lysimeter was significantly higher than on the East. Thus the 5-year average K_c, 0.53, for the East lysimeter is about 18% lower than the West lysimeter's average K_c of 0.65. The West lysimeter average K_c value of 0.65 for turfgrass, is about 16% higher than the previously used value of 0.56 (Hill, 1994).

TABLE 13: SOUTHGATE GOLF COURSE EAST AND WEST LYSIMETER FULL SEASON WATER BALANCE VALUES WITH SEASONAL CALCULATED CROP COEFFICIENTS

East Lysimeter										
Year	**Calc. Period**		**Irrig. + Rain (in)**	**Water Added (in)**	**Measured Drain. (in)**	**Adjusted Drain. (in)**	**ET (in)**	**ET_{rs} (in)**	**K_c**
	Begin	**End**							
2004	11-Jun	4-Dec	35.71	0	13.70	13.98	21.73	41.29	0.53
2005	10-Mar	2-Dec	33.22	13.59	3.33	12.18	34.63	63.38	0.55
2006	23-Jun	1-Dec	23.81	0	4.13	4.13	19.68	36.59	0.54
2007	24-Jan	29-Dec	54.97	2.60	15.22	17.35	40.22	74.73	0.54
2008	7-Feb	18-Nov	46.58	0.00	12.54	13.16	33.42	69.14	0.48
								Average K_c =	0.53
West Lysimeter								K_c St. Dev. =	0.03
Year	**Calc. Period**		**Irrig. + Rain (in)**	**Water Added (in)**	**Measured Drain. (in)**	**Adjusted Drain. (in)**	**ET (in)**	**ET_{rs} (in)**	**K_c**
	Begin	**End**							
2004	11-Jun	4-Dec	36.83	0	9.28	9.28	27.55	41.29	0.67
2005	10-Mar	2-Dec	41.91	7.81	10.23	9.47	40.25	63.38	0.64
2006	23-Jun	1-Dec	31.50	0	7.08	8.43	23.07	36.59	0.63
2007	24-Jan	29-Dec	69.48	1.73	19.51	21.17	50.04	74.73	0.67
2008	7-Feb	18-Nov	62.22	0	17.03	17.9	44.32	69.14	0.64
								Average K_c =	0.65
								K_c St. Dev. =	0.02
Site Average								Average K_c for all lysimeters =	0.59
								K_c St. Dev. for all lysimeters =	0.07

Spanish Fork

The Spanish Fork North lysimeter ET varied from 17.8 (2002) to 30.4 inches (2004), as given in Table 14. Calculated ET_{rs} varied from 31.7 to 49.7 inches. The observed K_c for the North lysimeter varied from 0.51 to 0.63, with a5-year average of 0.58. The South lysimeter ET was about the same as that for the North varying from 14.2 (2002) to 29.9 inches (2005). The observed K_c varied from 0.45 to 0.61, with a 5-year average of 0.54. The average K_c for all years over both lysimeters was 0.56, which is identical to the value previously used. No drainage adjustments were needed for either lysimeter at Spanish Fork.

TABLE 14: SPANISH FORK TURF PLOT NORTH AND SOUTH LYSIMETER FULL SEASON WATER BALANCE VALUES WITH SEASONAL CALCULATED CROP COEFFICIENTS

North Lysimeter									
Year	**Calc. Period Begin**	**Calc. Period End**	**Irrig. + Rain (in)**	**Water Added (in)**	**Measured Drain. (in)**	**Adjusted Drain. (in)**	**ET (in)**	**ET_{rs} (in)**	**K_c**
2002	5-Jun	3-Oct	18.73	0	0.96	0.96	17.77	31.67	0.56
2003	30-Apr	10-Nov	20.35	4.62	2.29	2.29	22.68	44.87	0.51
2004	1-Apr	10-Nov	34.16	6.13	9.90	9.90	30.39	48.33	0.63
2005	22-Mar	2-Nov	40.28	4.01	14.90	14.90	29.39	49.72	0.59
2006	24-Apr	11-Oct	32.13	6.48	10.15	10.15	28.46	45.35	0.63
								Average K_c =	0.58
								K_c St. Dev. =	0.05
South Lysimeter									
Year	**Calc. Period Begin**	**Calc. Period End**	**Irrig. + Rain (in)**	**Water Added (in)**	**Measured Drain. (in)**	**Adjusted Drain. (in)**	**ET (in)**	**ET_{rs} (in)**	**K_c**
2002	5-Jun	3-Oct	19.54	0	5.38	5.38	14.16	31.67	0.45
2003	30-Apr	10-Nov	22.93	4.62	5.09	5.09	22.46	44.87	0.50
2004	1-Apr	10-Nov	34.52	6.44	11.61	11.61	29.35	48.33	0.61
2005	22-Mar	2-Nov	35.04	6.18	11.35	11.35	29.87	49.72	0.60
2006	24-Apr	11-Oct	31.84	5.76	13.20	13.20	24.40	45.35	0.54
								Average K_c =	0.54
								K_c St. Dev. =	0.07
Site Average								Average K_c for all lysimeters =	0.56
								K_c St. Dev. for all lysimeters =	0.06

Sunbrook

Water use on the Sunbrook East lysimeter varied from 13 (2004) to 35.9 inches (2005) and K_c varied from 0.37 to 0.68, with a 5-year average of 0.49 (Table 15). The West lysimeter ET was similar, varying from 13.8 (2004) to 35.5 inches (2002). Calculated K_c varied from 0.33 to 0.64, with a 5-year average of 0.46. The average K_c for all years over both lysimeters was 0.47. These relatively low K_c values may reflect the data collection issues experienced at this site. Calculated ET_{rs} for Sunbrook varied from 29.7 to 71.3 inches. This wide range corresponds to the variable season length from year to year. Drainage adjustments were made in 2005 on both lysimeters.

The highest K_c values (0.68 and 0.64) were derived for the relatively short calculation period, late June through mid-October, 2006. The average two lysimeter K_c value of 0.66 for this 2 1/2 month period is essentially the same as the K_c (0.65) from the Southgate West lysimeter (Table 13).

TABLE 15: SUNBROOK GOLF COURSE EAST AND WEST LYSIMETER FULL SEASON WATER BALANCE VALUES WITH SEASONAL CALCULATED CROP COEFFICIENTS

East Lysimeter									
Year	**Calc. Period**		**Irrig. + Rain (in)**	**Water Added (in)**	**Measured Drain. (in)**	**Adjusted Drain. (in)**	**ET (in)**	**ET_{rs} (in)**	**K_c**
	Begin	**End**							
2002	25-Feb	5-Nov	35.12	0	0	0	35.12	71.33	0.49
2003	3-Feb	10-Nov	31.28	0	1.06	1.06	30.22	71.07	0.43
2004	1-Mar	29-Jun	13.6	0	0.62	0.62	12.98	35.17	0.37
2005	18-Jan	28-Dec	39.93	6.5	5.02	10.54	35.89	70.69	0.51
2006	26-Jun	16-Oct	25.44	0	5.34	5.34	20.10	29.73	0.68
								Average K_c =	0.49
								K_c St. Dev. =	0.12
West Lysimeter									
Year	**Calc. Period**		**Irrig. + Rain (in)**	**Water Added (in)**	**Measured Drain. (in)**	**Adjusted Drain. (in)**	**ET (in)**	**ET_{rs} (in)**	**K_c**
	Begin	**End**							
2002	25-Feb	5-Nov	35.46	0	0	0	35.46	71.33	0.50
2003	3-Feb	10-Nov	24.99	0	1.49	1.49	23.50	71.07	0.33
2004	1-Mar	29-Jun	13.78	0	0	0	13.78	35.17	0.39
2005	18-Jan	28-Dec	31.98	6.07	5.00	8.29	29.76	70.69	0.42
2006	26-Jun	16-Oct	23.50	0	4.62	4.62	18.88	29.73	0.64
								Average K_c =	0.46
								K_c St. Dev. =	0.12
Site Average								Average K_c for all lysimeters =	0.47
								K_c St. Dev. for all lysimeters =	0.11

ESTIMATED MONTHLY TURFGRASS CROP COEFFICIENTS

Deriving K_{cr} values for shorter than seasonal time periods resulted in poor results due to the temporal resolution of the lysimeter data (see page 23 herein). However, at the request of the Utah Division of Water Resources, monthly K_{cr}, and subsequently K_{co}, values were calculated for four of the lysimeters: Logan – New, Spanish Fork – North, and both Southgate lysimeters.

Data near the beginning and end of each month were adjusted in an attempt to attribute measured ET to the correct month. For example: if a lysimeter reading was made within the first few days of the month and no reading was made on the last day or two of the previous month the data was prorated between the 2 months using the number of days in the measurement interval. Further adjustments were made to the data upon final analysis by discarding obvious outliers from the average monthly Kc values.

Alfalfa Reference, ET_{rs}, Based Crop Coefficients

The year-to-year variation in monthly K_{cr} values at the four lysimeters is shown in Figures 10 through 13. Although there was considerable deviation in some points ("outliers"), i.e. November 2006, Logan New (Fig. 10); September 2002 and 2003 and March 2005, Spanish Fork North (Fig. 11); December 2006, Southgate East (Fig. 12) and December 2004, Southgate West (Fig. 13), there was general agreement in trends during the season.

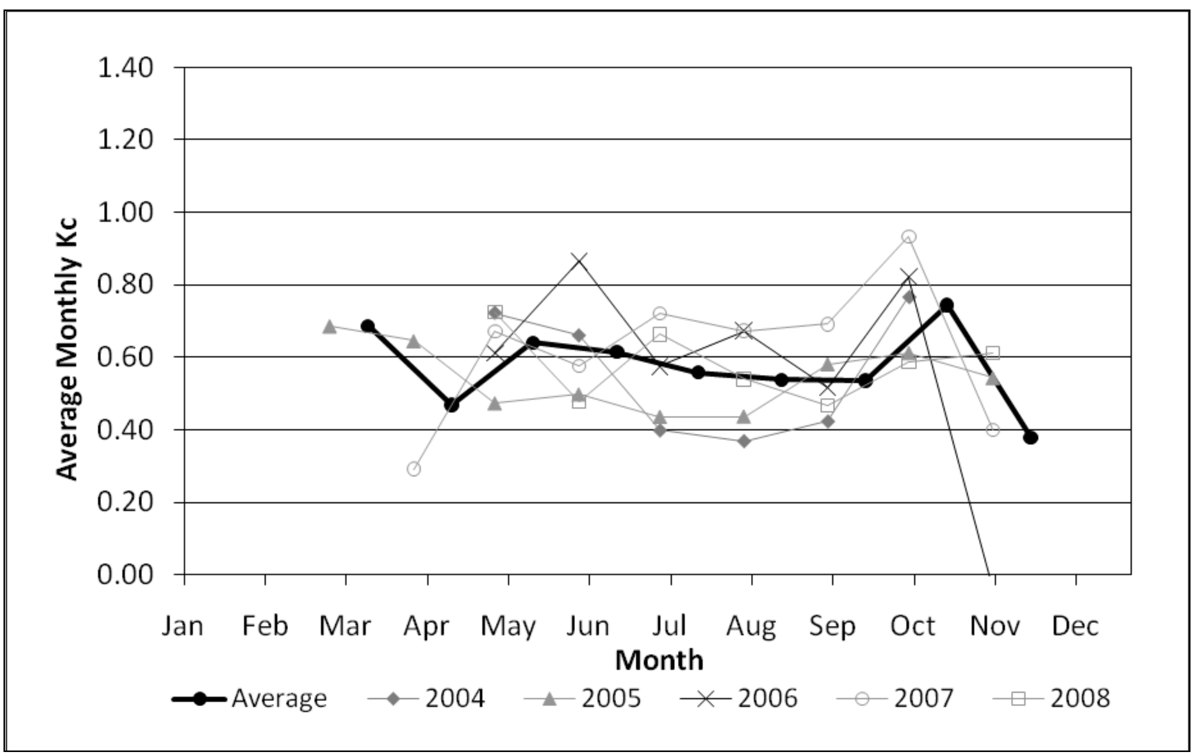

FIGURE 10. MONTHLY K_{CR} VALUES FOR THE LOGAN NEW LYSIMETER, 2004-2008

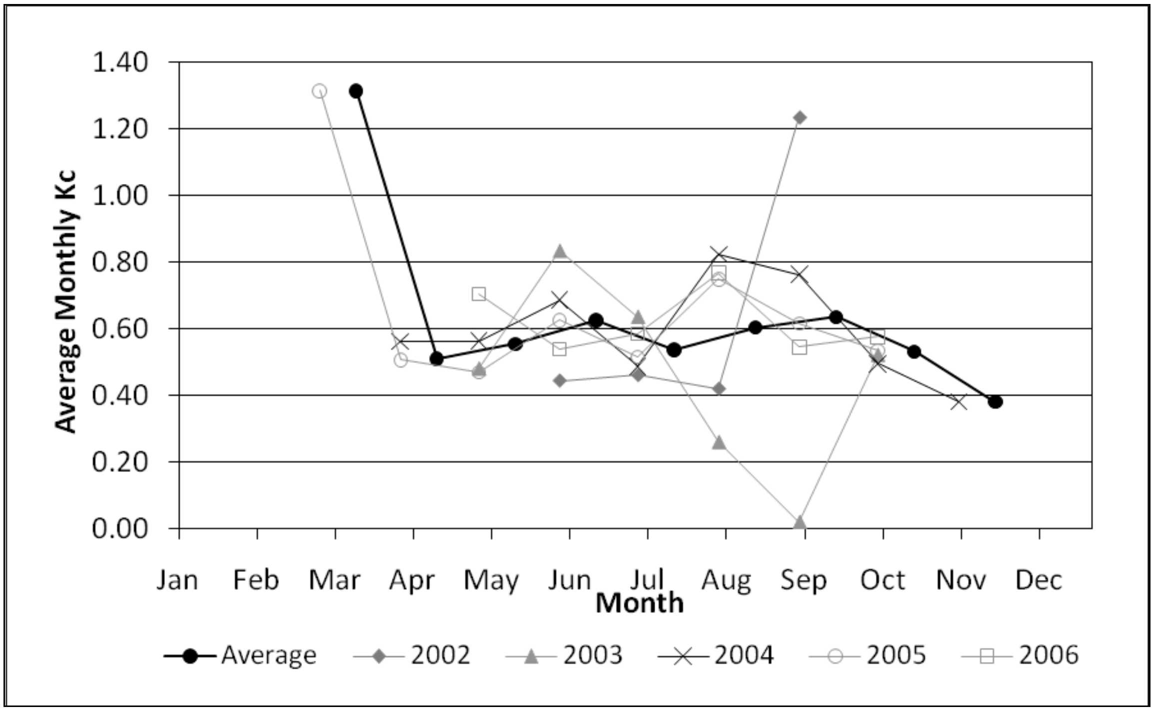

FIGURE 11. MONTHLY K_C VALUES FOR THE SPANISH FORK NORTH LYSIMETER, 2002-2006.

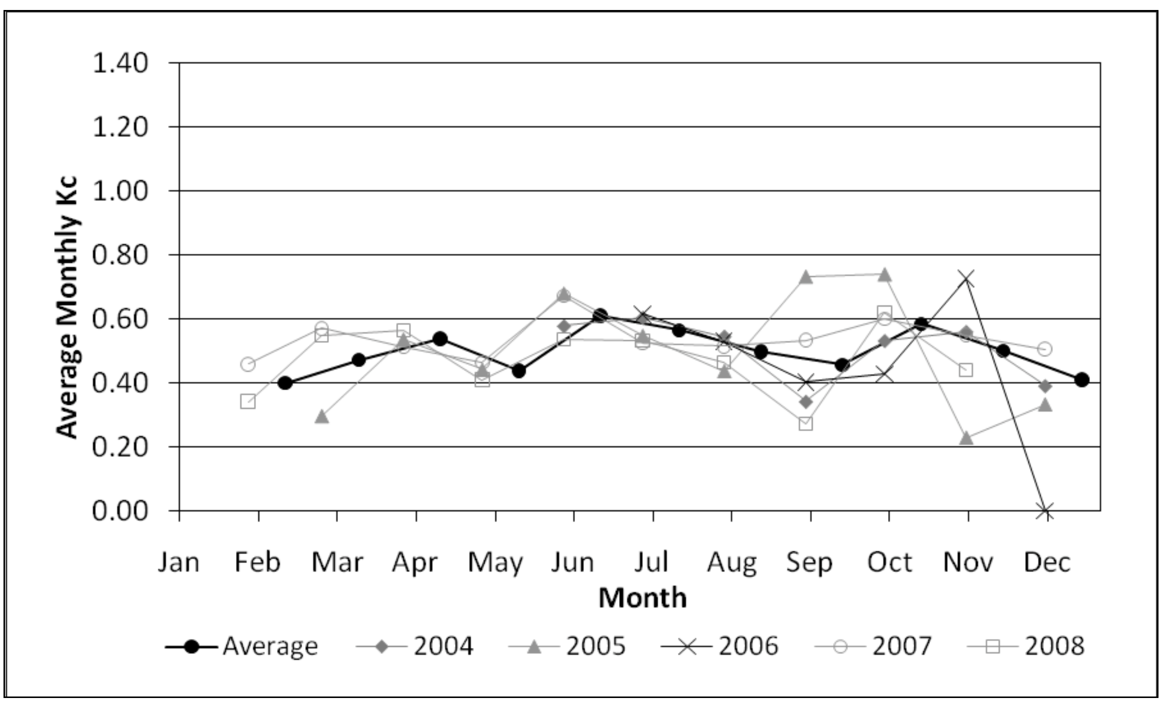

FIGURE 12. MONTHLY K_C VALUES FOR THE SOUTHGATE EAST LYSIMETER, 2004-2008.

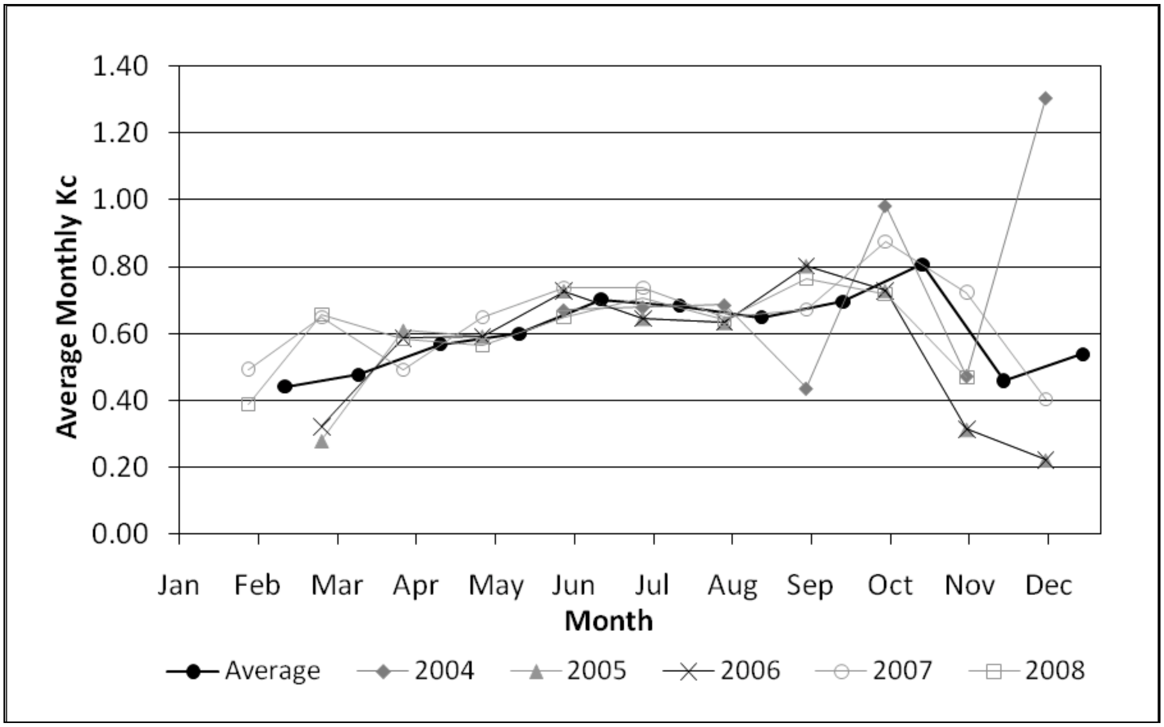

FIGURE 13. MONTHLY K_C VALUES FOR THE SOUTHGATE WEST LYSIMETER, 2004-2008.

Average K_{cr} values for each month at the four lysimeters are shown in Figures 14 through 17. The dashed lines in the figures represent the seasonal suggested K_{cr} values for the location. Seasonal K_{cr} values were 0.6 for Logan and Spanish Fork and 0.65 for Southgate. The outlying data points were not included in Figures 14 through 17.

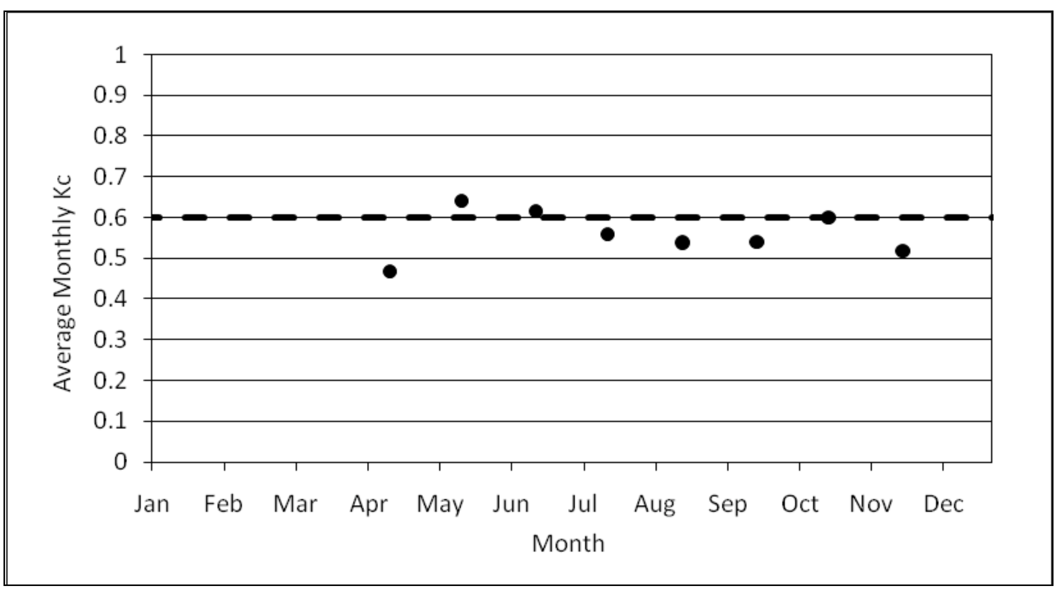

FIGURE 14. AVERAGE K_C VALUES FOR EACH MONTH FOR THE LOGAN NEW LYSIMETER. . OBVIOUS OUTLIERS WERE EXCLUDED. THE DASHED LINE REPRESENTS THE SUGGESTED FULL SEASON K_{CR}.

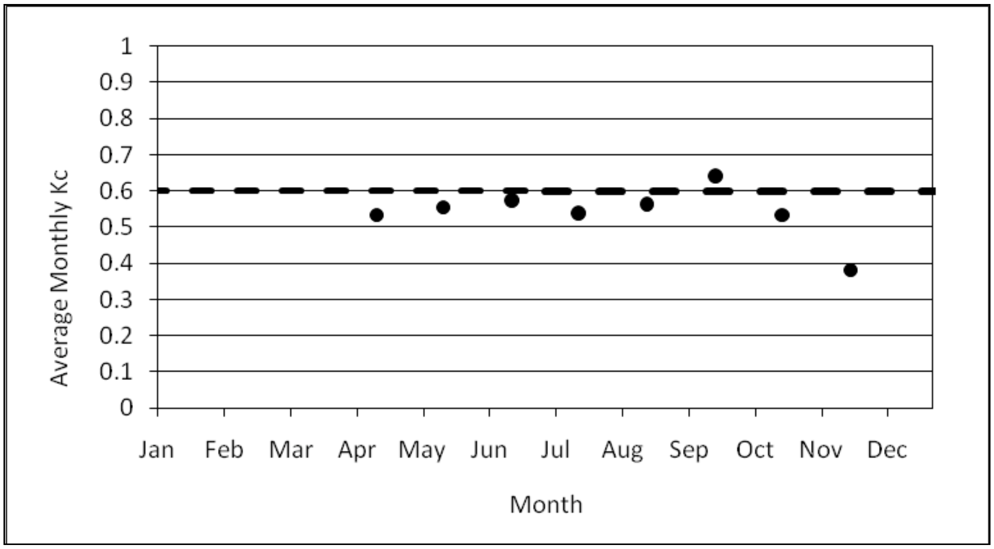

FIGURE 15. AVERAGE K_C VALUES FOR EACH MONTH FOR THE SPANISH FORK NORTH LYSIMETER. OBVIOUS OUTLIERS WERE EXCLUDED. THE DASHED LINE REPRESENTS THE SUGGESTED FULL SEASON K_{CR}.

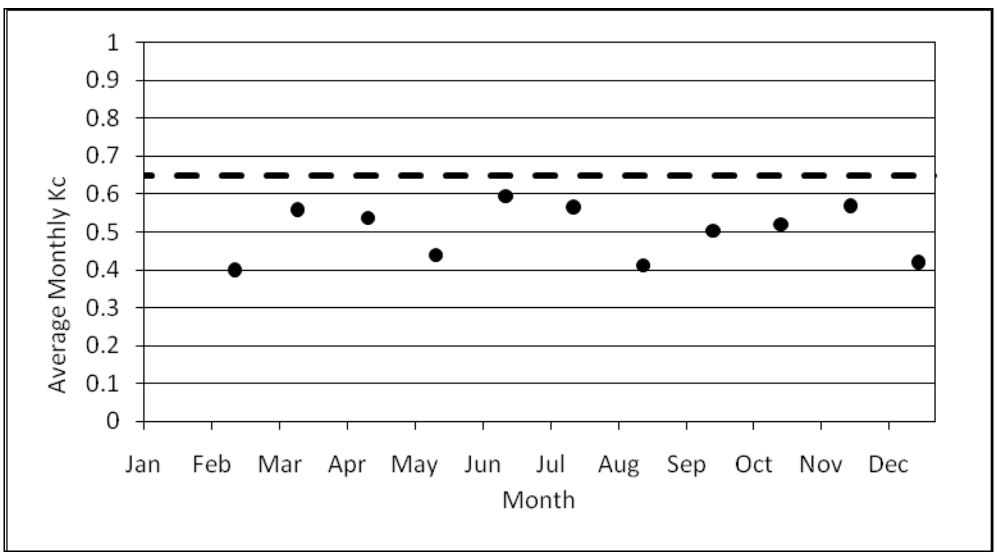

FIGURE 16. AVERAGE K_C VALUES FOR EACH MONTH FOR THE SOUTHGATE EAST LYSIMETER. OBVIOUS OUTLIERS WERE EXCLUDED. THE DASHED LINE REPRESENTS THE SUGGESTED FULL SEASON K_{CR}.

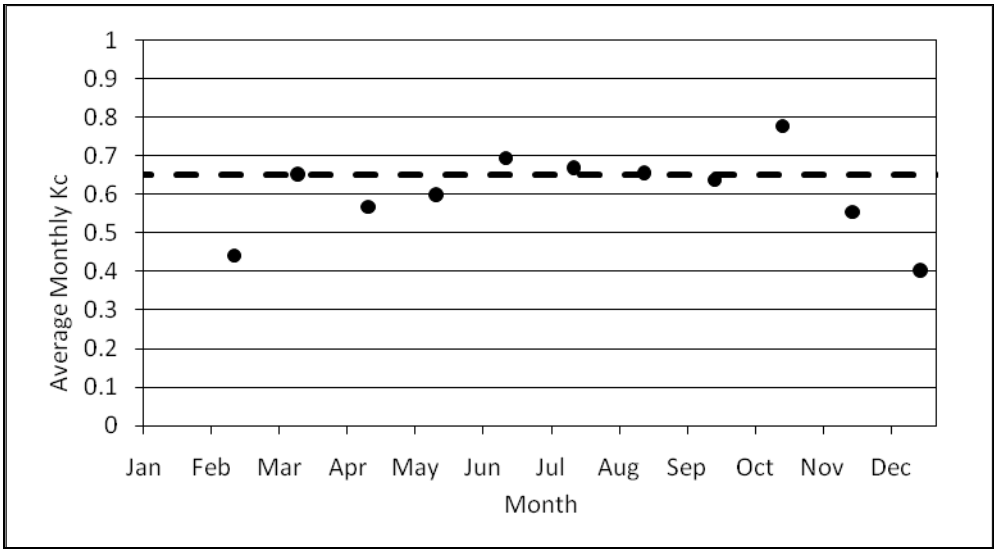

FIGURE 17. AVERAGE K_C VALUES FOR EACH MONTH FOR THE SOUTHGATE WEST LYSIMETER. OBVIOUS OUTLIERS WERE EXCLUDED. THE DASHED LINE REPRESENTS THE SUGGESTED FULL SEASON K_{CR}.

The values in Figures 14 and 15 were combined to obtain an average for the higher elevation regions of the state. The results of this comparison along with a suggested seasonally varying crop coefficient curve are shown in Figure 18. A similar curve, Figure 19, was developed for the low elevation southern region of the state.

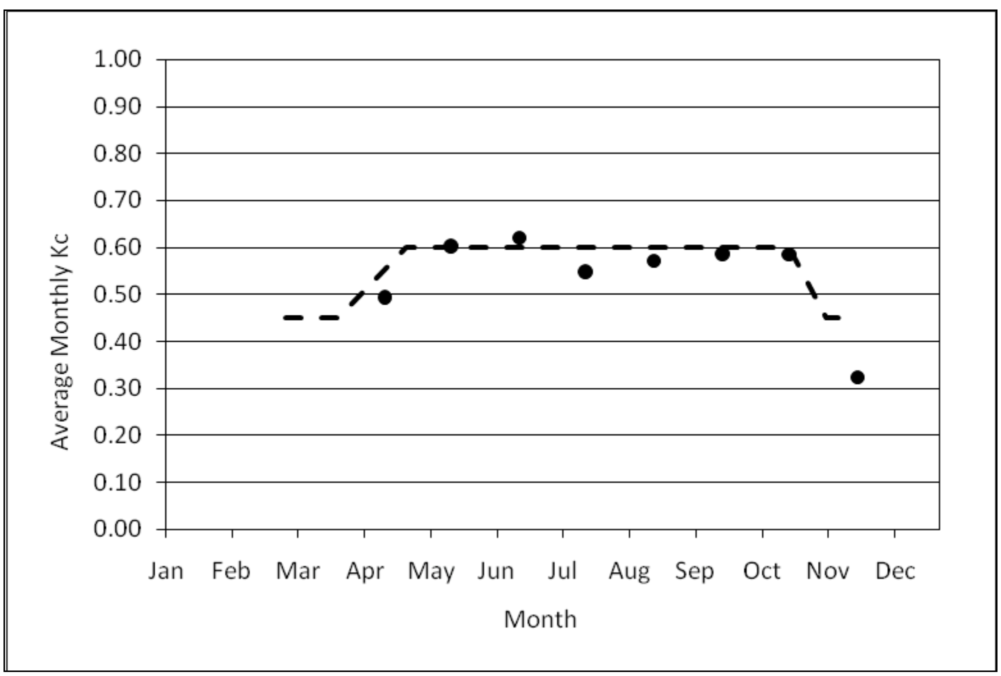

FIGURE 18. SUGGESTED K_C CURVE FOR THE HIGHER ELEVATION AREAS OF UTAH. MONTHLY K_C VALUES AVERAGED BETWEEN THE LOGAN NEW AND SPANISH FORK NORTH LYSIMETERS. OBVIOUS OUTLIERS WERE EXCLUDED.

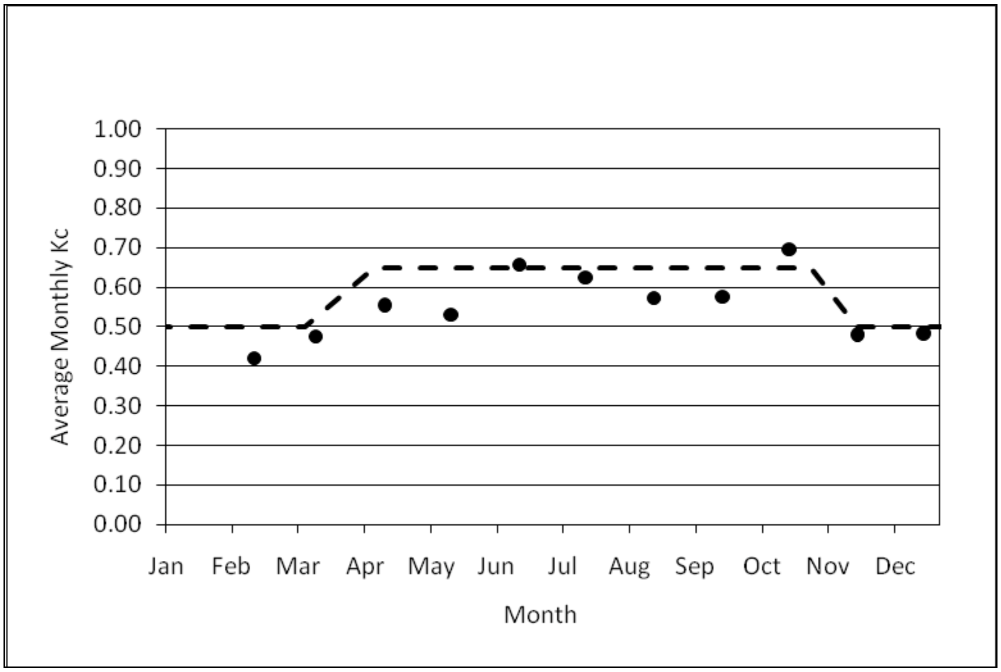

FIGURE 19. SUGGESTED K_C CURVE FOR THE LOW ELEVATION AREAS OF SOUTHERN UTAH . MONTHLY K_C VALUES AVERAGED BETWEEN THE TWO SOUTHGATE LYSIMETERS. OBVIOUS OUTLIERS WERE EXCLUDED.

The crop coefficients shown in Figures 18 and 19 are reasonable K_{cr} curves for different regions of Utah. The curve in Figure 18 represents the majority of the state (except the Southern Low elevation region of Utah's Dixie). The curve suggested in Figure 18 begins with a value of 0.45 starting at turf green up or absence of snow in the spring (around the beginning to middle of March for many areas). The K_{cr} remains at 0.45 for about 20 days until late March when the turf begins active growth. The K_{cr} value then increases linearly for about 30 days to a value of 0.60 when the turf reaches full leaf area and growth (typically near the end of April). The turf K_{cr} remains at 0.60 for the duration of the season until cool fall temperatures result in reduced turf growth rates. This is typically around mid-October, after which K_{cr} decreases linearly toward 0.45 in early November and remains at that value until dormancy.

The K_{cr} curve for Utah's Dixie, Figure 19, is similar to that of Figure 18, however, it continues for the full year and is shifted up by about 0.05. The K_{cr} begins in January at a value of 0.50 during the semi-dormant period. In late February to early March the K_{cr} value begins to increase linearly toward a value of 0.65, typically reached after about 30 days or within the first week of April. The K_{cr} value remains at 0.65 for the majority of the season until the growth slows in late fall. This occurs in mid to late October and the K_{cr} value decreases linearly toward a value of 0.50, which is typically reached in mid-November, and remains at 0.50 until the following spring. In both sets of suggested crop coefficient curves, Figures 18 and 19, maintaining the mid-season K_{cr} at a constant value, 0.60 or 0.65, ignores the indication of a "summer slump" in turf water use.

Grass Reference, ET_{os}, Crop Coefficients

Calculated values of ET for a grass reference, ET_o are lower than those for an alfalfa reference by 10 to 25% or so (Jensen, et al., 1990). As a result, grass reference based crop coefficient, K_{co}, values are correspondingly greater than alfalfa based crop coefficients, K_{cr}. Typically, multiplication factors on ET_o ranging from 1.15 to 1.25 have been used to approximate ET_r (for example, $ET_r = 1.2\ ET_o$). The crop coefficient values for ET_{rs} presented above should be multiplied by a factor approximately equal to 1.2 to relate to an ASCE Standardized grass reference, ET_{os}, basis. Thus, the mid-season K_{co} values are 0.72 (0.72 = 1.2 x 0.6) for higher elevations and northern Utah. Similarly, a mid-season K_{co} value of 0.78 (0.78 = 1.2 x 0.65) would be indicated for the southern and lower elevation parts of the state. The early and late season K_{co} values become 0.48 and 0.60, respectively, for the northern higher elevation and southern lower elevation sites. Mid-season K_{co} values of 0.70 for northern Utah and higher elevations and 0.80 for southern Utah and lower elevations are obtained from rounding these values to the nearest 0.05. Corresponding early and late season K_{co} values are 0.50 and 0.60, respectively, for the northern higher elevation and southern lower elevation sites. The resulting crop coefficient curves are shown in Figures 20 and 21.

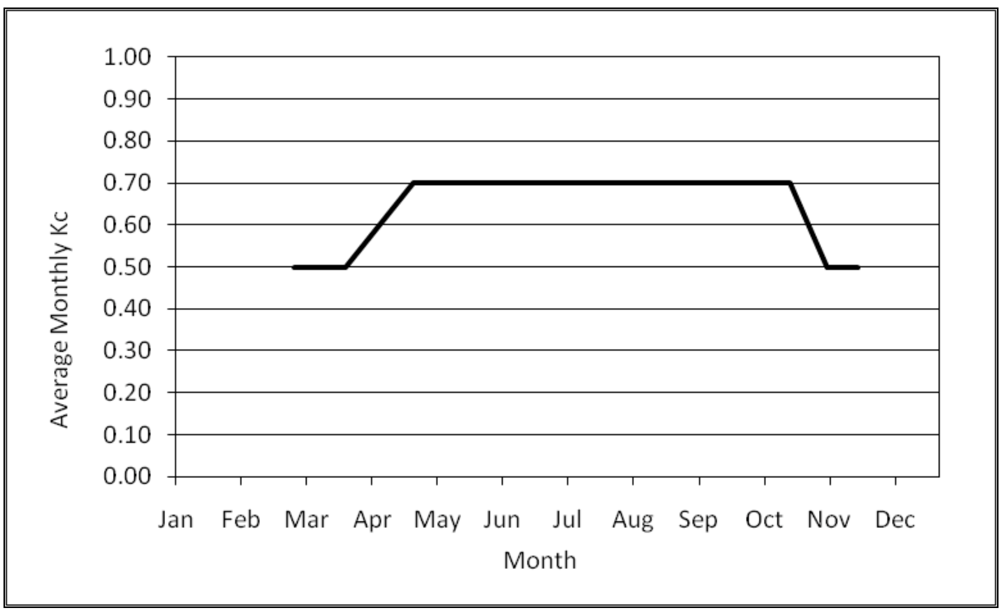

FIGURE 20. SUGGESTED K_{CO} CURVE FOR THE HIGHER ELEVATION AREAS OF UTAH ALONG WITH K_{CO} VALUES FOR EACH MONTH AVERAGED BETWEEN THE LOGAN NEW AND SPANISH FORK NORTH LYSIMETERS. ADAPTED FROM FIGURE 18.

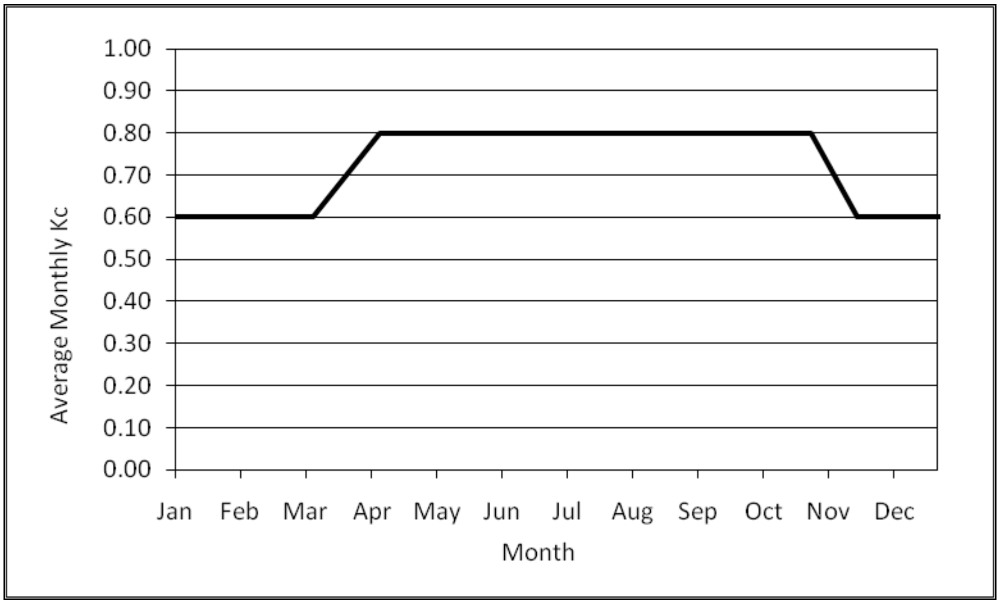

FIGURE 21. SUGGESTED K_{CO} CURVE FOR THE LOW ELEVATION AREAS OF SOUTHERN UTAH ALONG WITH K_{CO} VALUES FOR EACH MONTH AVERAGED BETWEEN THE TWO SOUTHGATE LYSIMETERS. ADAPTED FROM FIGURE 19.

SUMMARY AND CONCLUSIONS

Observed seasonal turfgrass consumptive use varied from 11.2 inches (Logan West, 2004, Table 11) to 50.0 inches (Southgate, 2007, Table 13). The range at Logan (Table 11) was 11.2 (West, 2004) to 35.2 inches (New, 2007); at Murray (Table 12), 22.2 (East, 2008) to 30.5 inches (East, 2005); at Southgate (Table 13), 19.7 (East, 2006) to 50.0 inches (West, 2007); at Spanish Fork (Table 14), 14.2 (South, 2002) to 30.4 inches (North, 2004) and 13.0 (East, 2004) to 35.5 inches (West, 2002) at Sunbrook (Table 15). Direct comparison of such variation in ET values across years and sites is problematic due to differing growing season lengths from year to year, site environmental conditions (average temperatures and wind patterns), and elevation (range of 2600 to 4800 ft above msl) from south to north in Utah (Latitude range of 37° N to 42° N).

There was considerable year to year and lysimeter to lysimeter variation. The year to year variation was more evident at Southgate and Sunbrook, due perhaps to the larger variation in calculation periods than at the other sites. The lysimeter to lysimeter variation was particularly noticeable at Logan comparing the West lysimeter to both the New and the East lysimeters. There was also a fair difference between the two lysimeters at Southgate. The variation in rain plus irrigation that is evident in Tables 11-15 between lysimeters at a given site illustrates non-uniformity of irrigation as there is proportionately lesser variation in the magnitude of rain amounts. It was also a perplexing data analysis issue.

The multi-year average seasonal observed (based only on individual lysimeter ET) crop coefficient values varied from 0.34 (Logan West) to 0.65 (Southgate West). Single season K_c values of 0.74 and 0.70 were calculated, respectively, for the East and West Murray lysimeters in 2005, but these seem anomalous and may be due to drainage measurement problems. A short period, 2-1/2 month, lysimeter average K_c of 0.68 was obtained at Sunbrook East (2006).

Study period average seasonal K_c values by lysimeter were: Logan 0.59 (New), 0.42 (East), 0.34 (West) and site average of 0.45; Murray 0.57 (both East and West) and site average of 0.57; Southgate 0.53 (East), 0.65 (West) and site average of 0.59; Spanish Fork 0.58 (North), 0.54 (South) and site average of 0.56 and Sunbrook 0.49 (East), 0.46 (West) and site average of 0.47. Average two lysimeter seasonal K_c values at Murray and Spanish Fork were similar (0.57 and 0.56, respectively) although there was less across year variation at Spanish Fork.

Ignoring the older lysimeters at Logan, the 5-year seasonal average K_{cr} on the New lysimeter of about 0.60 may reasonably represent a well-watered turfgrass, cutting height of 1.5 to 2 inches, in the central and northern parts of the state, whereas the Southgate West lysimeter 5-year seasonal average K_{cr} of 0.65 would similarly be reasonable to use in the lower elevation and warmer southern Utah. These K_{ct} values, 0.60 and 0.65, are, respectively, about 7% and 16% higher than the K_c of 0.56 used in earlier estimates of turfgrass evapotranspiration across Utah (Hill, 1994).

Further analysis was conducted to derive monthly K_{cr} and subsequently K_{co}, values for four of the lysimeters: Logan – New, Spanish Fork – North, and both Southgate lysimeters. Lysimeter ET data near the beginning and end of each month were prorated between the 2 months using the number of days in the measurement interval. Further data adjustments were made upon final analysis by discarding obvious outliers from the average monthly Kc values

The turfgrass crop coefficient for the majority of the state (except low elevation southern Utah) begins with a value of 0.45 starting at turf green up or absence of snow in the spring (around the beginning to middle of March for many areas). The K_{cr} remains at 0.45 for about 20 days until late March when the turf begins active growth. The K_{cr} value then increases linearly for about 30 days to a value of 0.60 when the turf reaches full leaf area and growth (typically near the end of April). The turf K_{cr} remains at 0.60 for the duration of the season until cool fall temperatures result in reduced turf growth rates. This is typically around mid-October, after which K_{cr} decreases linearly toward 0.45 in early November and remains at that value until dormancy.

The K_{cr} curve for Utah's Dixie is similar; however, it continues for the full year and is shifted up by about 0.05. The K_{cr} begins in January at a value of 0.50 during the semi-dormant period. In late February to early March the K_{cr} value begins to increase linearly toward a value of 0.65, typically reached after about 30 days or within the first week of April. The K_{cr} value remains at 0.65 for the majority of the season until the growth slows in late fall. This occurs in mid to late October and the K_{cr} value decreases linearly toward a value of 0.50 which is typically reached in mid-November and remains at 0.50 until the following spring. In both sets of suggested crop coefficient curves, maintaining the mid-season K_{cr} at a constant value, 0.60 or 0.65, ignores the indication of a "summer slump" in turf water use.

Grass reference-based crop coefficient, K_{co}, values were derived from K_{cr} by multiplying K_{cr} by about 1.2. Thus, the mid-season K_{co} values are 0.72 (0.72 = 1.2 x 0.6) for higher elevations and northern Utah. Similarly, a mid-season K_{co} value of 0.78 (0.78 = 1.2 x 0.65) would be indicated for the southern and lower elevation parts of the state. The early and late season K_{co} values become 0.48 and 0.60, respectively, for the northern higher elevation and southern lower elevation sites. Mid-season K_{co} values of 0.70 for northern Utah and higher elevations and 0.80 for southern Utah and lower elevations are obtained from rounding these values to the nearest 0.05. Corresponding early and late season K_{co} values are 0.50 and 0.60, respectively, for the northern higher elevation and southern lower elevation sites.

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APPENDICES

APPENDIX A: Work Tasks by Objective

A. Determine turfgrass water use by measurement with lysimeters.

USU:

1. Arrange for fabrication and transport lysimeters each site.
2. Supervise installation of lysimeters at each site and provide overall supervision of project.
3. Train personnel at each site in irrigation precipitation, weather, and lysimeter data collection and data transfer protocol.
4. Receive weekly e-mailed lysimeter data reports from each site, enter into spreadsheet and perform preliminary quality control analysis.
5. Perform weekly preliminary data analysis for quality control for all sites, collect lysimeter and weather data at Logan site.
6. Prepare annual progress reports. Analyze available weather data from electronic weather stations and associated NWS stations and prepare consistent daily and monthly data sets and share interim results as appropriate.
7. Provide ongoing training and supervision as needed.
8. Perform detailed analysis of first two years of lysimeter data after November 2002 and prepare interim turfgrass crop coefficient and water use recommendations.
9. Prepare final report summarizing the lysimeter data from Cache Valley, south Salt Lake County, Utah County, and Washington County.

BYU:

1. Perform lysimeter data collection at BYU turf plots beginning in early March and continuing through November. The frequency should be at least once per week in spring and fall and twice (or three times) per week in the summer.
2. Collect other site data as appropriate (see Annex).
3. E-mail current data to USU each week.
4. Review reports, provide suggestions for improvement.

B. Analysis of previously collected turfgrass irrigation and soil water content data.

BYU:

1. Locate and organize archived data.
2. Transmit in electronic format (standard DOS - ASCII or Excel or Quattro) to USU BIE personnel.
3. Review preliminary results and draft of final report.

USU:

1. Review, screen, and perform detailed analysis of neutron probe, irrigation, precipitation, and weather data as received from BYU.
2. Prepare summary report of findings.

APPENDIX B: Turf Lysimeter Data Collection Protocol

The purpose of this protocol is to formalize turfgrass lysimeter data collection procedures. This will aid in obtaining turfgrass water use under well-watered conditions. Well-watered conditions are assured only if drainage occurs from time to time.

I. Data Collection Procedure and Observations

A. Rain gage

The rain gage top funnel should be removed. The inner measurement cylinder should be taken out and held up such that the water surface is at eye level. The amount of water (hundredths of inches) should be recorded on the data sheet. If more than 1 inch of irrigation and precipitation occurs, the inner cylinder should be dumped (equals 1 inch at overflow), and water poured into it from the rain gage to get the reading. The total depth should be recorded on the data sheet.

B. Drainage Bucket

The bucket should be removed from the manhole well, and set on a level surface (perhaps the manhole lid). The depth of water should be measured with a tape measure to the nearest 1/16 inch in two diametrically opposite sides of the bucket (to allow for non-level). The two depths (h1, h2) should be recorded on the data sheet. Alternately, a graduated cylinder could be used to obtain water volumes in place of the two depth measurements.

C. Data Sheet

Date	East Lysimeter				West Lysimeter				Comments
	Rain Gage Depth		Drainage bucket depth (inch)		Rain Gage Depth		Drainage bucket depth (inch)		
	NW (inch)	SE (inch)	h1,h2	Avg	NW (inch)	SE (inch)	h1, h2	Avg	

D. Data Collection Interval.

Data should be collected from the rain gages and drainage bucket for each lysimeter at least once per week. However, if the drainage buckets are allowed to overflow, the water balance measurement will be lost for that time period. Thus, the lysimeter data collection interval may need to be 2 or 3 days, rather than once per week, if abundant drainage is occurring or may occur due to heavy rain or irrigation.

At the time of data collection, clean any grass leaves that may be encroaching on the rain gage outer pipes. Also, note any conditions that may affect data accuracy.

II. Springtime Data Collection Initiation (except at St. George, which is year round)

As soon as the snow has melted, the rain gages should be cleaned and placed in an upright position with the top as close to level as possible and about 1 inch below the ground surface. Any grass should be trimmed away from the inside of rain gage access pipe (6 inch PVC). The drainage buckets should also be placed under the drain pipe. The date and time of start-up should be recorded and faxed [(435) 797-1248] or e-mailed (bobh@ext.usu.edu) to R. W. Hill.

Within a day or two, check the drainage bucket for any drainage water. If no drainage occurs, then a measured quantity of water (15 gallons) should be added to each lysimeter. If the soil is moist, the drainage buckets should be checked in 30 minutes. Any drainage should be noted and measured if more than 1/3 full, and the buckets emptied. Use judgment to estimate when the buckets should be checked again to avoid overflow.

III. Growing Season Observations

Weekly lysimeter data collection visits should begin in the spring and continue throughout the summer and fall. Depending on the amount of drainage, the visits may need to be twice weekly to avoid having a drainage bucket overflow in between observations. At each visit, data should be collected as described in Section I. The data sheet should be faxed to [(435) 797-1248] to R.W. Hill, every 2 or 3 weeks.

It is important to the purpose of the study that adequate water be applied to the lysimeters. Thus, some drainage is necessary to ensure "well-watered" conditions have been realized. If drainage is not occurring each week, then the addition of extra water to each lysimeter must be done. If no drainage occurs, then a measured quantity of water (15 gallons) should be added to each lysimeter. If the soil is moist, the drainage buckets should be checked in 30 minutes. Any drainage should be noted and measured if more than 1/3 full, and the buckets emptied. Use judgment to estimate when the buckets should be checked again to avoid overflow. Also, this procedure should be followed to induce drainage at the end of each month (April, May, June, July, August and September) if no other drainage has occurred.

IV. Winter Shut Down (except at St. George)

The rain gage should be turned upside down, or removed from the field, when temperatures become cold enough to cause freezing damage. The measurement should be discontinued if significant snow fall occurs. The drainage buckets could be left in place a little longer, without frost damage. Although, they eventually should also be turned upside down when air temperatures drop below about 20°F.

APPENDIX C: Weather Station Sensors and Observation Parameters

Each electronic weather station included a Campbell Scientific data logger (CR10X at Logan, Murray, Southgate and Sunbrook and CR10 at Spanish Fork) and the following sensors:

- Two Campbell Scientific 107 Temperature Probes, one for air and one for soil temperature
- Vaisala HMP 45C Relative Humidity Probe
- LI COR LI200s Silicon Pyranometer, for solar radiation
- Met One 014A Anemometer and Met One 024A Wind Direction Sensor (at Logan, Murray and Spanish Fork) or R M Young 05103 Wind Monitor (at Sunbrook and Southgate), for wind speed and wind direction

The data logger scanned the various input sensors once every 10 seconds. These observations were processed and output as daily (midnight to midnight) and hourly values. The parameters output each hour and each 24 hour period were:

Hourly

- Average air temperature
- Maximum air temperature
- Minimum air temperature
- Average relative humidity
- Total solar radiation
- Average wind speed
- Average wind direction
- Average soil temperature

24 Hour (once daily) Output

- Maximum air temperature
- Minimum air temperature
- Maximum relative humidity
- Minimum relative humidity
- Total solar radiation
- Total wind run
- Average wind direction
- Average soil temperature

APPENDIX D: Summary of Data Collected at Logan, 1991-2001

TABLE D1: SEASONAL TOTAL IRRIGATION, DRAINAGE AND TURF WATER USE, 1991-95,2000-01, FROM TWO LYSIMETERS IN THE LOGAN GOLF AND COUNTRY CLUB, LOGAN, UTAH. PARTIAL SEASON DATA FOR 1996-99

		East Lysimeter			West Lysimeter			
Year	Season	Irrigation + rain, in	Drainage in	ET in	Irrigation + rain, in	Drainage in	ET in	Average ET, inches
1991	03 Apr-28 Oct	38.95	6.81	32.14	38.00	13.94	24.06	28.10
1992	15 Apr-27 Oct	28.29	0.18	28.11	28.69	2.97	25.72	26.92
1993	16 Apr-26 Oct	30.77	6.36	24.41	34.87	15.75	19.12	21.77
1994	11 Apr-28 Oct	35.08	3.94	31.14	37.80	14.71	23.08	27.10
1995	17 Apr-02 Oct	27.48	1.59	25.89	32.17	11.06	21.11	23.50
2000	06 Apr-06 Nov	35.70	2.11	33.59	32.73	8.67	24.06	28.83
2001	15 Mar-19 Nov	44.24	11.39	32.84	42.08	20.64	21.44	27.14
Seven Year Average		34.36	4.63	29.73	35.19	12.53	22.66	26.19
1996[b]	09 May-14 Nov	25.93	3.75	22.18	27.64	8.46	19.18	20.68
1997[b]	09 May-03 Dec	25.52	6.47	19.05	13.25	4.75	8.50	13.78
1998[b]	16 Apr-11 Nov	22.61	2.87	19.74	15.91	5.39	10.52	15.13
1999[b]	11 May-08 Sept	17.97	0.66	17.31	8.73	1.57	7.16	12.24

[a] The two lysimeters are located at the Logan Golf and Country Club in a rough between the hole one and three fairways and adjacent to the greens nursery area. The electronic weather station (Campbell Scientific, Inc.) is west of the greens nursery and about 30 feet to the north of the east lysimeter.

[b] Some drainage records lost due to bucket overflow.

TABLE D2: TURFGRASS WATER USE (ET) AND CROP COEFFICIENTS (K_{CM}), 1991-95, AND 2000-01, FROM LYSIMETERS AT THE LOGAN GOLF AND COUNTRY CLUB, LOGAN, UTAH. PARTIAL SEASON DATA FOR 1996-99

	East Lysimeter			West Lysimeter			
Year	ET_r Inches	ET, inches	K_{cm}	ET_r inches	ET, inches	K_{cm}	Seasonal average K_{cm}
1991	43.06	32.14	0.75	43.06	24.06	0.56	0.65
1992	48.82	28.11	0.58	48.82	25.72	0.53	0.55
1993	47.36	24.41	0.52	47.36	19.12	0.40	0.46
1994	52.00	31.14	0.60	52.00	23.08	0.44	0.52
1995	40.75	25.89	0.64	40.75	21.11	0.52	0.58
2000	48.37	33.59	0.69	48.37	24.06	0.50	0.60
2001	47.53	32.84	0.69	47.53	21.14	0.45	0.57
Seven year Average	46.84	29.73	0.63	46.84	22.61	0.48	0.56
1996	33.90	22.18	0.65	32.91	19.18	0.58	0.62
1997	40.77	19.05	0.47	20.84	8.50	0.41	0.44
1998	28.56	19.74	0.69	21.70	10.52	0.49	0.59
1999	27.17	17.31	0.69	16.93	7.16	0.42	0.53
Eleven Year Average			0.63			0.48	0.56

1. Weather Data for 1996 was obtained from Logan USU Station
2. 1995 data started from May instead of April
3. For 1996, 97, 98 and 1999 some drainage records lost due to bucket overflow

APPENDIX E: Corrections Made to Weather Data

Logan

2002 Daily calculations only were done for the whole year, Day 35 hour 1500 appears twice with different data the first was deleted.

2003 Daily calculations only were done for days 1 – 31, Day 31 values were erroneous except for maximum temperature; all other values were taken as an average of Days 30 and 32.

2007 Day 95 hour 1100 was taken as an average of hours 1000 and 1200, Day 304 hours 600 and 700 appeared twice with different data the second 600 and first 700 were deleted.

2008 Day 86, hour 600 was missing (daylight savings shift) an average of hours 500 and 700 was used to create a 600 data set. Day 309 hour 900 appeared twice (daylight savings shift) took average of both lines and used it.

Murray

2003 Daily calculations only were done for days 1 – 30, Day 30 had some erroneous values for minimum temperature, relative humidity (max and min) and solar radiation; these values were taken as an average of days 29 and 30.

2004 Day 336 hour 600 data was duplicated, one of these lines was deleted

2005 Day 303 hour 900 appeared twice with different data the first was deleted.

2006 Day 42 had error values for minimum temperature and relative humidity as soil temperature; average values from days 42 and 44 were used. On Day 100 the day was falsely incremented up by one until Day 103 (which appeared twice) this was corrected. This same error was corrected between days 142 and 150. Day 101 hour 2300 was estimated as an average of hours 2200 and 2400.

2007 Day 333 data was replaced with the average of Days 332 and 334.

2008 Data up to Day 25, hour 600, was 6 hour data due to an accidental program alteration. Data from Day 25, hour 1500 on was hourly, daily calculations were used for Days 1 – 25. Daily wind and solar radiation values for Day 25 were taken as an average of Days 24 and 26, because the program change caused a loss of temporary data in the logger on Day 25. Day 72, hour 600 was missing (daylight savings shift) an average of hours 500 and 700 was used to create a 600 data set. Day 311 hour 700 appeared twice (daylight savings shift). Took average of both lines and used it.

Southgate

2004 Day 303 hour 900 appeared twice with different data. The first was deleted.

2005 Day 122 hour 800 appeared identically twice. One was deleted, Day 124 hours 600 to 800 were filled in with data from Sunbrook

2006 Day 67 hour 1600 minimum temperature was missing the value from 1700 was used. Hour 1500 all data was missing the averages of values for 1400 and correctecd1600 were used. Daily values (except maximum air temperature) were taken as averages of days 66 and 69. Day 93 hour 12 was taken as an average of hours 1100 and 1300.

2008 Day 70, hour 700 was missing (daylight savings shift) an average of hours 600 and 800 was used to create a 700 data set.

Spanish Fork

2002 Day 61 hour 2100 values were taken as an average of 2000 and 2200. Day 16 hour 1000 average air temperature and relative humidity as well as minimum air temperature were taken as averages from 800, 900, 1100, and 1200. Day 29 hour 1500 average air temperature and relative humidity as well as minimum air temperature were taken as averages from 1300, 1400, 1600, and 1700. Day 122, hour 1600 values were taken as an average of 1500 and 1700. Day 67 hour 200 values were taken as an average of 100 and 300. Day 136 hour 700 values were taken as an average of 600 and 800. Day 172, hour 200 values were taken as an average of 100 and 300. Day 152, hour 1500 average air temperature and relative humidity as well as minimum air temperature were taken as averages from 1400 and 1600. Day 189, hour 1400 was repeated with different data the second was deleted. Day 207, hour 200 values were taken as an average of 100 and 300. Day 223, hour 200 values were taken as an average of 100 and 300. Day 241 hour 200 values were taken as an average of 100 and 300. Day 252 hour 1300 was repeated with different data. The second was deleted.

2003 Daily calculations only were done for days 1 – 30. For days 114 to 365, data was saved every two hours, wind was saved as mph, this was multiplied by two to get wind run for 2 hours. Day 36 daily values were taken as an average of days 35 and 37, except maximum relative humidity. Day 113 minimum daily air temperature was taken as an average of days 112 and 114.

2004 All data was saved every 2 hours. Wind was saved as mph and multiplied by 2 to get wind run for 2 hours.

2005 Data up to Day 124 was saved every 2 hours, wind was saved as mph and multiplied by 2 to get wind run for 2 hours. Day 31, hour 1600 to Day 34 were missing averages from days 28-30 and 35-37 were used to fill in the daily gap. Day 124 minimum daily air temperature and humidity as well as solar radiation and soil temperature vales were taken as an average from days 123 and 135.

2006 Replica data between days 137 and 179 was deleted.

Sunbrook

2002 Day 98 hour 1200 was taken as an average of hours 1100 and 1300.

2003 Day 28 all daily values except maximum air temperature and wind, were taken as averages from days 27 and 29. Days 175 to 179 were duplicated, as were day 189 hour 300 to day 194 hour 1300, the duplicates were deleted.

2004 Day 336 minimum air temperature and relative humidity values were taken as averages of days 335 and 337. Day 306 hour 600 appears twice with different data the second line was deleted. Day 307 hour 600 appears twice with different data. The second line was deleted.

2005 Some hourly values weren’t saved from days 1 to 28, daily calculations only, were done for this period. Day 336 hour 900 was missing minimum air temperature, the value from 800, was used. Day 76 hour 600 appears twice with different data. The second line was deleted.

2006 Temperature data from day 252 at hour 200 to day 256 at hour 1200 and day 257 at hour 1200 had errors, this data was replaced with data from Southgate.

APPENDIX F: Adjustments Made to Individual Lysimeter Drainage Values Due to Overtopping

Logan

The new (East) lysimeter was installed in 2004 with data collection beginning in early May (Table 9). Drainage adjustments were made to the 2004 and 2005 data. At Logan the maximum volume the drainage buckets could hold was equivalent to 0.81 inches of water applied over the area of the lysimeter. Over topping events occurred on September 3, 2004, March 28, 2005, April 28, 2005, drainage for these events was adjusted to 1.25, 1.54, and 1.74 inches, respectively. An overtopping event also occurred on June 10, 2005, but the model showed that no change was necessary so it was left at 0.81 inches.

Drainage adjustments for the East lysimeter were made for every year except 2004 (Table 10). The dates of the overtopping events and adjustments for this lysimeter in 2002 were: April 30 was adjusted to 1.00, June 24 to 0.91, and September, 8 to 1.58. On September 2, 2003, an overtop event was estimated to be 0.99 inches, this was found by the model to be an over estimate so the drainage was adjusted to 0.82 inches. For 2005 an overtop event on March 25 was adjusted to 1.65 inches. Two overtop events were recorded in 2006, on July 1 and September 15. The drainage on July 1 was not adjusted, the other, however, was adjusted to 2.01 inches. In 2007 two adjustments were made, one on June 7 to 1.48 inches and one on July 26 to 1.06 inches. An event on July 2, 2007 was not adjusted.

Adjustments were made for all years for the West lysimeter (Table 11). In both 2002 and 2003 the adjusted drainage values are lower than the reported values because both years had large numbers of over top events, seven in 2002 and 5 in 2003. In both years four values did not need adjusting, but had been over estimated when they were initially recorded. These values were all adjusted to 0.82 inches. This happened on June 7, 14, and 17 and July 15, 2002, as well as April 21, June 14, August 18 and 22, 2003. Other 2002 overtop events occurred April 30, June 4, and September 8. These events were adjusted to 1.58, 0.92, and 1.01 inches, respectively. One event was adjusted in 2003, on September 29. It was changed to 0.95 inches.

Two overtop events were adjusted in 2004, on May 13, adjusted to 1.10 inches, and September 3, adjusted to 1.44 inches. An event on July 16, 2004 was not adjusted. For 2005, five events were not adjusted, they occurred on July 15 and 18, August 29, and September 2 and 9. Events on March 28 and April 28 were changed to 1.69 and 1.95 inches, respectively. Drainage values for September 15 and October 8, 2006 were adjusted to 2.06 and 1.24 inches. Five other events in 2005 on: May 24 and 30, July 25, August 17, and September 20, were not adjusted. Four overtop events occurred in 2007, of which two were adjusted. Events on June 7 and October 9 were changed to 1.53 and 1.16 inches. The other two events occurred on July 2 and 30.

Murray

Because of deficit irrigation, very few drainage events occurred for each calculation period at Murray; thus any abnormal drainage had a significant effect on the calculated crop coefficient. This was the case in 2005, therefore K_c values for this year are considerably higher than values calculated for other years.

For both lysimeters no drainage adjustments were needed for the years 2003 through 2005. However, a drainage bucket overtop event occurred on both lysimeters on November 4, 2004. These events were not adjusted and were left at 0.97, the equivalent depth over the lysimeter corresponding to the maximum volume which the drainage buckets could hold. For the East lysimeter (Table 12) adjustments were made for Jun 21, 2007, changed to 4.47 inches, and July 5, 2007, changed to 2.59 inches.

Three adjustments were made to drainage values for the West lysimeter at Murray (Table 13). The first was on June 21, 2006, which was adjusted to 1.31 inches. A second occurred on July 5, 2007, and was adjusted to 1.10 inches. The third event, on July 9, 2007, may have been a missing data value. A drainage value of 0.53 inches was added for that date.

Southgate

Drainage adjustments were made each year for both lysimeters at Southgate (Tables 14 and 15), with the exception of East lysimeter in 2006. In 2004 overtop events occurred twice at the East lysimeter. One occurred on June 26, this was adjusted to 1.04 inches. The other event occurred on October 29; it was not adjusted but was left at 0.97, the equivalent depth corresponding to a full drainage bucket. Two overtop events occurred in 2005 (September 27 and October 24). The first was not adjusted, but the second was changed to 1.82 inches. During this same year the model showed significant drainage on three days, for which the record showed no drainage. Because there were some errors in data collection these anomalies were treated as overtop events. They occurred on May 5, July 21, and September 22; drainage values of 3.27, 5.26, and 3.74 inches, respectively, were used days. In 2007 four overtop events occurred, no adjustments were made the first two, on July 6 and August 29. The other two events were on September 22, changed to 1.45 inches, and December 2, changed to 1.52 inches.

For the West lysimeter an overtop event occurred June 26, 2004, on. The data for this event was not adjusted. An overtop event was recorded on October 24, 2005; this was changed to 2.25 inches. In 2005 the West lysimeter had anomalies similar to those described for the East lysimeter. They also occurred on May 5, June 2, and July 21. The drainage abnormalities in May and July were adjusted to 3.36 and 4.14 inches, respectively. The anomaly in June was not adjusted.

Spanish Fork

No overtop events were recorded for either lysimeter at Spanish Fork for any year.

Sunbrook

Adjustments were only made for 2005 (See Tables 18 and 19). For the East lysimeter overtop events occurred on February 28, August 8, and September 18, 2005. The event on February 28 was adjusted to 4.19 inches and that on September 18 to 1.07 inches. The event in August was not changed. Abnormalities were present in the 2005 drainage records similar to those present at Southgate for the same year. These occasions were also treated as overtop events and were adjusted accordingly. The adjustments were made on May 5, to 1.93 inches, and July 21, to 2.40 inches.

Two overtop events occurred in 2005 on the West lysimeter, one on February 28 and another on August 8. Neither event was adjusted. The abnormalities on May 5, and July 21, were present, however, and values of 1.21 and 2.39 inches were inserted for these times.

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